Aluminum Alloy Castings

Properties, Processes, and Applications

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The Materials Information Society

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

First printing, December 2004

Comments, criticisms, and suggestions are invited and should be forwarded to ASM International.

Prepared under the direction of the ASM International Technical Books Committee (2003-2004), Yip-Wah Chung, FASM, Chair.

ASM International staff who worked on this project include Scott Henry, Senior Manager of Product and Service Development; Charles Moosbrugger, Technical Editor; Bonnie Sanders, Manager of Production; Carol Polakowski, Production Supervisor; and Pattie Pace, Production Coordinator.

Library of Congress Cataloging-in-Publication Data

Kaufman, J. G. (John Gilbert), 1931-
Aluminum alloy castings properties, processes and applications/J. Gilbert Kaufman, Elwin L. Rooy.
p. cm.
Includes bibliographical references and index.
ISBN 0-87170-803-5
1. Aluminum alloys—Mechanical properties. 2. Aluminum castings. I. Rooy, Elwin L. II. title.

TA480.A6K33 2004
620.1'86—dc22

2004052923

ISBN: 0-87170-803-5
SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America

Preface

This book is intended to provide a comprehensive summary of the physical and mechanical properties of most types of aluminum alloy castings. It includes discussion of the factors that affect those properties, including composition, casting process, microstructure, soundness, heat treatment, and densification. Extensive previously unpublished technical data including aging response, growth, fatigue, and high- and low-temperature performance have been consolidated with existing and updated materials property characterizations to provide a single authoritative source for most performance evaluation and design needs.

The consideration of casting process technologies is intentionally limited to typical capabilities and to their influence on property performance. Many excellent references are available for more detailed information and guidance on production methods and on important aspects of melting, melt processing, solidification, and structure control. Interested readers are referred to the publications of the American Foundry Society (AFS), the North American Die Casting Association (NADCA), and the Non-Ferrous Founders' Society (NFFS). Many of these publications are included in the reference lists at the end of each chapter.

It is also beyond the scope of this book to provide more than generalized economics of aluminum casting production.

The authors gratefully acknowledge the support and assistance of several organizations and individuals in developing this volume. Alcoa, Inc. generously provided extensive previously unpublished production and property data from their archives, adding significantly to the industry's shared knowledge base. We wish, especially, to thank R.R. Sawtell and R.J. Bucci of Alcoa for their cooperation in arranging the release of this material. We are pleased that the American Foundry Society has been credited as co-publisher of this book. The AFS Aluminum Division Review Committee provided substantive and constructive suggestions; the members of the committee are listed in these pages. In addition, Laura Moreno and Joseph S. Santner of AFS provided content from AFS publications and arranged for the necessary permissions to reproduce information as needed. We would also like to thank Joseph C. Benedyk of the Illinois Institute of Technology for his helpful comments, and John C. Hebeisen of Bodycote for his assistance in providing the results of recent studies in hot isostatic processing. The North American Die Casting Association and the Non-Ferrous Founders' Society also gave us permission to cite, with appropriate references, information from their publications. We also acknowledge the support and assistance of the Aluminum Association, Inc., notably, permission to include information from their publications covering aluminum casting alloys.

J. Gilbert Kaufman
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About the Authors

J.G. (Gil) Kaufman has a background of almost fifty years in the aluminum and materials information industries and remains an active consultant in both areas. In 1997, he retired as vice president, technology, for the Aluminum Association, Inc., headquartered in Washington, D.C., and is currently president of his consulting company, Kaufman Associates. Earlier in his career, he spent twenty-six years with the Aluminum Company of America and five with ARCO Metals, where he was vice president, R&D. He also served as president and CEO of the National Materials Property Data Network, establishing a worldwide online network of more than twenty-five materials databases. Mr. Kaufman is a Fellow and Honorary Member of ASTM, and a Fellow and Life Member of ASM International. He has published more than 125 articles, including four books, on aluminum alloys and materials data systems.

Elwin Rooy retired after thirty-five years with the Aluminum Company of America, where he was corporate manager of metallurgy and quality assurance, to form a consulting firm specializing in aluminum process and product technologies, quality systems, and industry relations. He has been active in committees of the Aluminum Association, American Foundry Society, American Die Casting Institute, The Institute of Scrap Recycling Industries, Society of Die Casting Engineers, ASM International, and TMS. He has served as chairman of the TMS Aluminum Committee, chairman of the AFS Light and Reactive Metals Division, director and chairman of the Northeast Ohio chapter of AFS, regional director of the Foundry Education Foundation, and charter member of the Drexel/WPI Advanced Casting Research Laboratory. Mr. Rooy's honors include the AFS award for Scientific Merit, The TMS/AIME Distinguished Service Award, the M.C. Flemings Award for contributions in the field of solidification, and the Arthur Vining Davis Award for technical achievement. He has served on the editorial boards of the *Journal of Metals* and *Advanced Materials & Processes*, published more than thirty articles and papers, edited *Light Metals 1991*, and authored or coauthored articles in the *ASM Handbook* series.

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DOI:10.1361/aacp2004p001

CHAPTER 1

Introduction

1.1 Background and Scope

It is the objective of this book to comprehensively summarize material properties and engineering data for aluminum alloy castings and to address the need for a single reference that covers production, quality assurance, properties, and applications of aluminum alloy castings.

Unlike most sources, the content addresses not only conventional sand and permanent mold castings, but also pressure die castings and many of the variations of all three that have developed over the years.

The physical and mechanical properties of aluminum castings may be altered through:

- *Alloying composition:* The composition of alloys determines the potential for achieving specific physical and mechanical properties. Alloy content is designed to produce characteristics that include castability as well as desired performance capabilities. The interaction of alloying elements is recognized in promoting desired microstructural phases and solid-solution effects for the development of these properties.
- *Cooling rate during and after solidification:* The conditions under which solidification takes place determine the structural features that affect the physical and mechanical properties of an alloy.
- *Casting process:* There are a large number of casting processes, and each imposes different rates of heat extraction, solidification rates, and means of compensating for solidification-related microstructural and macrostructural tendencies.
- *Solidification:* Engineered castings are susceptible to internal and superficial defects. The complex geometries of shaped castings, fluid dynamics, and solidification mechanics combine to present unique and difficult challenges to the objective of dense, discontinuity-free parts. Internal porosity can result from shrinkage and hydrogen porosity, as well as from visually detectable defects such as misruns, cracks, moisture reactions, folds, and tears. Nonmetallic inclusions affect mechanical properties and nucleate hydrogen pore formation. Pore volume fraction and the geometry and distribution of internal voids reduce tensile properties, fatigue strength, toughness, and ductility, while surface defects strongly influence mechanical and fatigue performance.
- *Heat treatment:* Mechanical properties can be altered by postsolidification thermal treatment, including annealing, solution heat treatment, and precipitation aging.
- *Postsolidification densification:* Hot isostatic processing (HIP) of castings can result in improved levels of internal soundness, higher tensile properties, ductility, and fatigue performance.

These factors and their effects are considered in Chapters 2 through 7, and a comprehensive summary of the mechanical and physical properties of aluminum alloy castings is provided in Chapter 8.

1.2 History

Castings were the first important market for aluminum, following the commercialization of the Hall-Heroult electrolytic reduction process. At first, applications were limited to curiosities such as house numbers, hand mirrors, combs, brushes, tie clasps, cuff links, hat pins, and decorative lamp housings that emphasized the light weight, silvery finish, and novelty of the new metal. Cast aluminum cookware was a welcome alternative to cast iron and brass pots, pans, and kettles. The cost of aluminum steadily declined, and by the end of the 19th century important engineering applications became economically viable.

Aluminum in cast as well as wrought forms was a metal for its time. Three emerging markets coincided with the appearance of aluminum as a material alternative:

- Electrification demanded not only low-density, corrosion-resistant, high-conductivity wire and cable for which aluminum was well-suited, but also transmission towers and cast installation hardware.
- Automotive pioneers sought innovative materials and product forms to differentiate the performance and appearance of their products.
- When the Wright Brothers succeeded in powered flight, engine and other parts in cast aluminum represented the beginning of a close collaboration with what would become the aviation and aerospace industries.

The large number of applications for which aluminum competed in these and other markets required the development of specialized compositions and material conditions to satisfy specific engineering requirements. The characterization of physical and mechanical properties and the results of performance testing were the basis for continuous new alloy developments and refinements in composition control. The development of permanent mold and pressure die casting as alternatives to sand casting encouraged the development of new alloys suited not just to application requirements but also to the

casting process. Continuing technological improvements in alloy, casting, and recycling technology have improved the competitiveness and enhanced the growth of aluminum castings markets.

1.3 Advantages and Limitations of Aluminum Castings

Aluminum castings are produced in a range of alloys demonstrating wide versatility in the characteristics than can be achieved. More than 100 compositions are registered with the Aluminum Association, and more than 300 alloys are in international use. Properties displayed by these alloys, without considering the expanded capabilities of metal-matrix and other composite structures, include:

Tensile strength, ksi (MPa)	10–72 (70–505)
Yield strength, ksi (MPa)	3–65 (20–455)
Elongation, %	<1–30
Hardness, HB	30–150
Electrical conductivity, %IACS	18–60
Thermal conductivity, Btu · in./h · ft^2 · °F at 77 °F (W/m · K at 25 °C)	660–1155 (85–175)
Fatigue limit, ksi (MPa)	8–21 (55–145)
Coefficient of linear thermal expansion at 68–212 °F (20–100 °C)	9.8–13.7 × 10^{-6}/°F (17.6–24.7) × 10^{-6}/°C)
Shear strength, ksi (MPa)	6–46 (42–325)
Modulus of elasticity, 10^6 psi (GPa)	9.5–11.2 (65–80)
Specific gravity	2.57–2.95

An ability to produce near-net-shape parts with dimensional accuracy, controlled surface finish, complex geometries including internal passages, and properties consistent with specified engineering requirements represents significant manufacturing advantages (Fig. 1.1, 1.2):

- In many cases, multicomponent welded or joined assemblies can be replaced with a single cast part.
- Machining requirements are reduced.
- Aluminum castings display controlled variations in as-cast finish.
- Contrasts between as-cast and machined finishes can be highlighted to create pleasing cosmetic effects.
- Capital requirements are typically less than for wrought products.
- Tooling can range from simple patterns to complex tool steel dies depending on product requirements and production volume.
- Metallurgically or mechanically bonded bimetal parts can be routinely cast.
- Aluminum parts are routinely cast by every known process, offering a broad range of volume, productivity, quality, mechanization, and specialized capabilities.
- Most aluminum casting alloys display solidification characteristics compatible with foundry requirements for the production of quality parts.

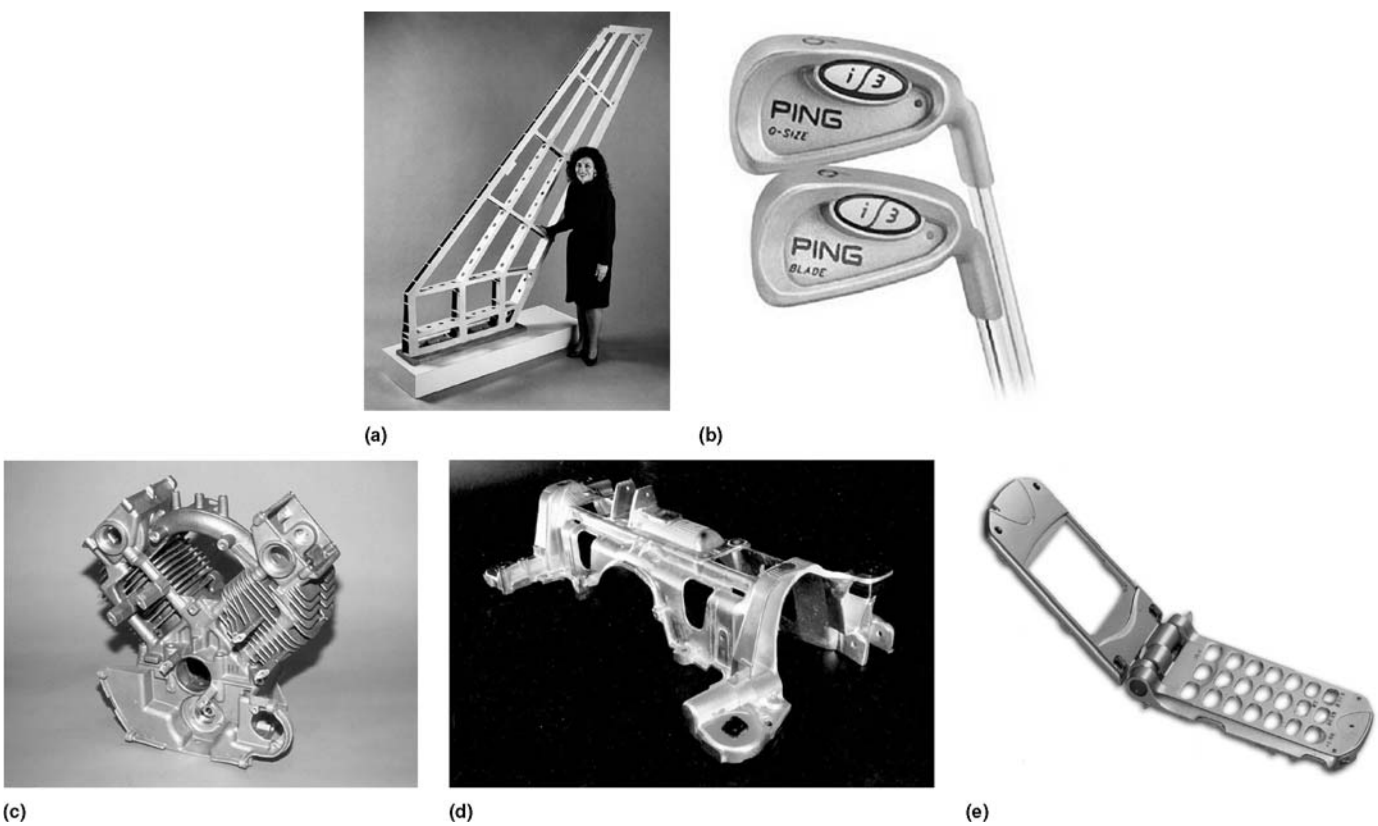

Fig. 1.1 Casting applications include innovative and complex designs serving the needs of diverse industries. (a) Aircraft stabilizer. (b) Golf irons. (c) Crankcase for small engine. (d) Cross member for a minivan. (e) Cellular phone casing. Source: Ref 1

- Many aluminum casting alloys display excellent fluidity for casting thin sections and fine detail.
- Aluminum casting alloys melt at relatively low temperatures.
- Aluminum casting processes can be highly automated.

Many limitations do apply. Very thin sections may not be castable. There are practical limitations in size for specific casting processes. The solidification behavior of some alloys precludes casting in difficult engineered configurations or in specific casting processes. The casting process is simpler and less capital intense than processes for producing forgings, extrusions, and rolled products. However, solidification in complex geometrical shapes, as with other fabrication options, can result in surface discontinuities and internal microstructure features with varying degrees of quality that affect properties and performance.

Aluminum alloy castings can display the tensile properties of most forgings, extrusions, and rolled plate. Because wrought products are normally characterized by finely recrystallized grain structures with specific anisotropy and highly textured microstructural features, ductility in longitudinal directions is typically greater than in castings that contain coarser grain structures. Conversely, the typically uniaxial grain structure and absence of anisotropy in cast structures do not present design engineers with the challenges associated with transverse property limitations.

1.4 Major Trends Influencing Increased Use of Aluminum Castings

1.4.1 Technology

The importance of improved energy efficiency in recent decades reflects the effects of increased gasoline and oil costs to the consumer and graduated government-mandated fuel-efficiency standards for automobile and truck manufacturers. Environmental concerns, global competitiveness, and raw-material concerns reinforce the incentives to reduce fuel consumption while preserving product performance and cost objectives.

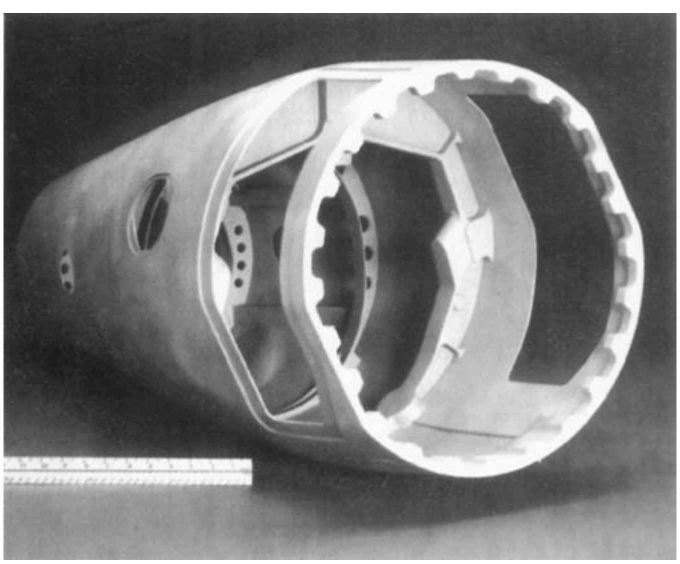

Fig. 1.2 One-piece cast missile tail cone. A cost-effective and reliable alternative to what had been a multicomponent assembly

The most cost-effective means of addressing these challenges has been the substitution of lightweight materials in existing and projected automotive designs. The U.S. automotive industry in collaboration with suppliers and the U.S. Department of Energy formed coalitions, including USAMP, which focused on materials characterization, and USCAR, which focused on materials development and process capabilities. Their objective has been to facilitate the transition to lighter-weight materials and more fuel-efficient performance without sacrifice in safety and with minimal impact on cost

The emphasis placed on improved efficiency in energy-consuming applications has resulted in a steady increase in the production and use of aluminum castings. The recent pattern of growth in aluminum casting shipments in the United States, including projections through the year 2005 is (Ref 2):

	Casting shipments in the United States	
Year	10^6 lb	10^6 kg
1994	2880	1306
1995	2990	1356
1996	3260	1479
1997	3380	1533
1998	3490	1583
1999	3550	1610
2000	3640	1651
2001	3800	1724
2202	4100	1860
2003	4500	2041
2004	4900	2223
2005	5160	2341

Cast aluminum has been used or demonstrated successfully for many decades in power-train applications including engine blocks, cylinder heads, pistons, transmission cases, and oil pans. In the first wave of light-weighting, aluminum was extensively adopted for these parts. For maximum impact on fuel efficiency, this expansion in the role of cast aluminum necessitated substitutions in more critical structural parts requiring the qualification of new component designs, materials, and production methods. These applications include traditionally cast iron, malleable iron, nodular iron and steel cross members, suspension and control arms, brackets, brake valves, rotors, and calipers. The commercialization of aluminum-intense automobile designs can result in 20 lb less engine emissions over the life of an automobile for each pound of iron or steel replaced by lower-density aluminum with correspondingly significant reductions in fuel consumption (Ref 3). New aluminum-intensive automotive construction concepts include cast fittings or nodes for extruded stringers in monocoque assemblies and the development of energy-absorbing thin-wall cast space frames. Figures 1.3 through 1.6 summarize the results of a study performed for the Aluminum Association showing the growth in cast aluminum as well as total aluminum products in North American light vehicle production.

The most significant barrier to the acceptance of cast aluminum in these and many other structural applications has been its reputation for variability. Overcoming this barrier required the demonstration of integrity and reliability derived from the evolu-

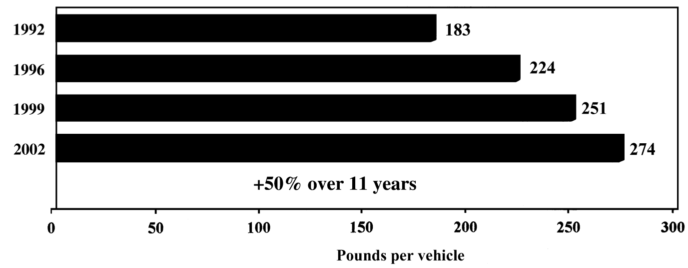

Fig. 1.3 North American light vehicle change in aluminum content, 1991 to 2002

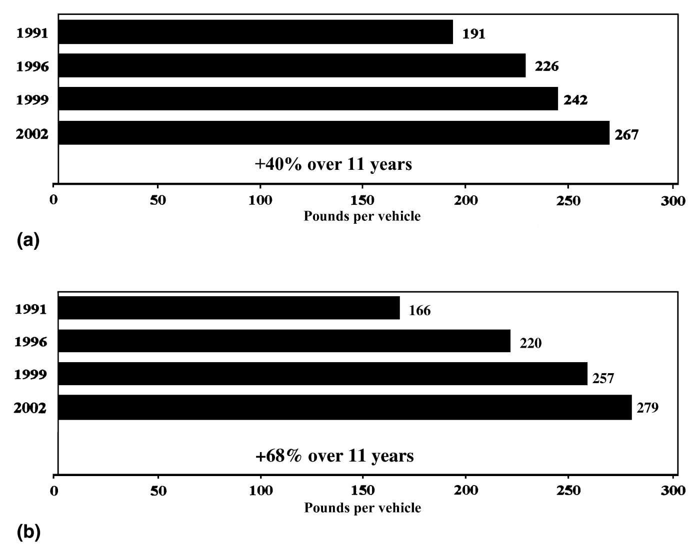

Fig. 1.4 North American light vehicle change in aluminum content, 1991 to 2002. (a) Passenger cars. (b) Trucks

tion of manufacturing processes and effective process controls. To be economic, casting results must be consistent and predictable without reliance on extensive inspection and nondestructive evaluation.

Each step in these developments has been the product of close collaboration between aluminum casting suppliers and the automotive industry. Not only are specific engineering criteria to be met for each new component, process designs and controls must reliably demonstrate capability and consistent product quality in the high volumes that are required. New casting processes, alloys, composite compositions, thermal treatments, process control methodologies, and the sensors and controls they require have contributed to an accelerated evolution of technologies that has been facilitated by research and development programs, many of which were sponsored by USCAR and USAMP in cooperation with national laboratories, colleges, and universities and with supplier industries.

Aluminum castings will play an important future role when inevitable electric, hybrid, or fuel-cell technologies are developed to combine materials, design, and construction methods for maximum efficiency.

Technological progress achieved in automotive programs affects all phases of aluminum foundry operations and all casting applications. Technology is also being broadly advanced by the activities of the U.S. Department of Energy that has identified metal casting as one of nine important "Industries of the Future." Benefits have been the development of a technology roadmap (Ref 4) that includes many of the challenges and technical barriers facing the aluminum castings industry and the funding of research and development programs in casting, aluminum, sensors, automation, and industrial materials of the future to meet or overcome them.

The product of these efforts has been greater versatility and improved capability in consistently and economically meeting even the most severe engineering challenges in automotive and other industries. Understanding the material and process changes that are

Aluminum product form	1999 lb/vehicle	Percent of total	2002 lb/vehicle	Percent of total	Percent change 1999 vs 2002
Die castings	95.76	38.2%	101.42	37.1%	+5.9% or 5.66 lb
Permanent mold castings	92.43	36.9%	100.58	36.8%	+8.8% or 8.15 lb
Flat rolled products	27.24	10.9%	29.39	10.7%	+7.9% or 2.15 lb
Extruded and drawn products	16.83	6.7%	18.49	6.8%	+9.9% or 1.66 lb
Forgings and impacts	6.34	2.5%	6.10	2.2%	–3.8% or –0.24 lb
Sand, lost foam, squeeze, and semisolid castings	11.94	4.8%	17.52	6.4%	+46.7% or 5.58 lb
Total	**250.54**	**100%**	**273.50**	**100%**	**+9.2% or 22.96 lb**

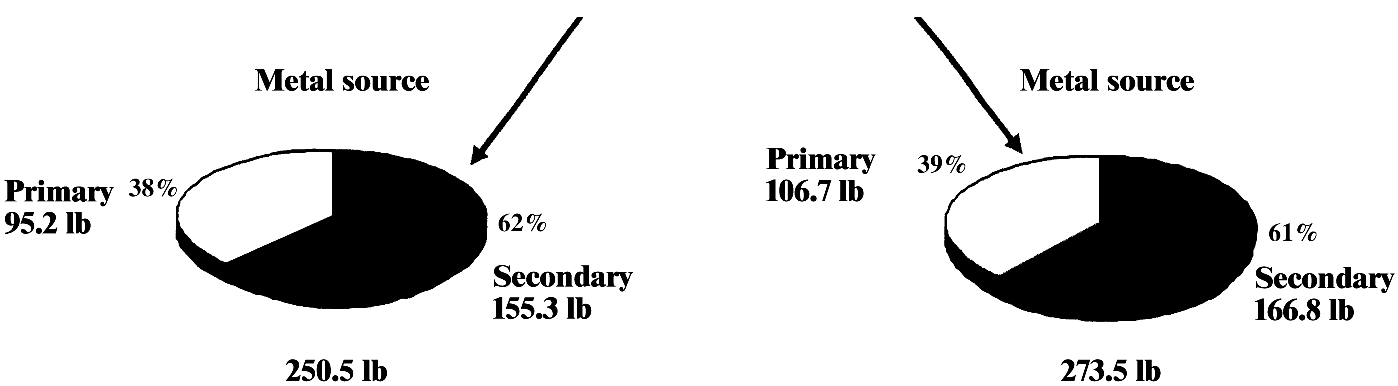

Fig. 1.5 North American light vehicle change in aluminum content by product form and metal source, 1999 to 2002

taking place to further increase the comfort of design engineers in the use of aluminum castings is essential for defining material advantages for any new application.

1.4.2 Recycling

Recycling and its impact in life-cycle studies are increasingly important considerations in materials selection (Ref 5). The manner in which energy efficiency can be directly and indirectly affected is important, but so are environmental and competitive considerations. While the production of aluminum is energy-intensive, it can be efficiently recovered from scrap at 5% of the energy required for reduction. Corrosion resistance preserves metal value, and new technologies are being developed for the segregation of scrap streams by alloy and product form for essentially closed-loop recycling.

Virtually all aluminum forms classified as old scrap (end of cycle) and new scrap (turnings, borings, gates and risers, rejections) are recyclable. With appropriate recycling processes, recoveries typically exceed 90%.

Many casting compositions are compatible with the alloy content of even mixed scrap. The cost of ingot produced from scrap is typically less than that of primary metal. As a consequence, most aluminum alloy castings are produced from recycled metal.

The use of aluminum in energy-consuming applications provides efficiencies with calculable benefits for prolonging product life, conserving raw materials, reducing energy consumption in manufacturing and service, reducing levels of environmental pollution and the costs of environmental control, and lowering material cost through recycling. When factored into cost comparisons with competing materials, the advantage of aluminum in life-cycle analysis can be significant.

1.5 Selecting the Right Aluminum Alloy and Casting Process

The succeeding chapters review the substantial portfolio of aluminum casting alloys available; Chapter 2 illustrates the characteristics that have made certain alloys the first choice for specific applications. Chapters 3 through 7 focus on the process and thermal treatment variables that influence the metallurgical structure of aluminum alloys and, in turn, how the combination of process variables and metallurgical structure influence their properties and performance. Finally, Chapter 8 provides a broad range of physical and mechanical property data, a substantial amount of which has never been published before, certainly not all in a single resource.

This wide range of information contained herein is provided as a reference for aluminum alloy casting producers, heat treaters, designers, and users with the intent of aiding them in the selection of the right alloy, temper, and processing needed to achieve the performance required of cast components. The authors believe it is clear that, as suggested above, aluminum casting alloys provide a broad range of capabilities including—when appropriate, process-optimization and quality-control procedures are applied—components suitable for challenging applications where soundness, strength, and toughness are critical. The authors hope it will also be clear that there are great advantages for designers and casting suppliers working closely with their customers on the selection of alloys, tempers, and casting processes capable of meeting manu-

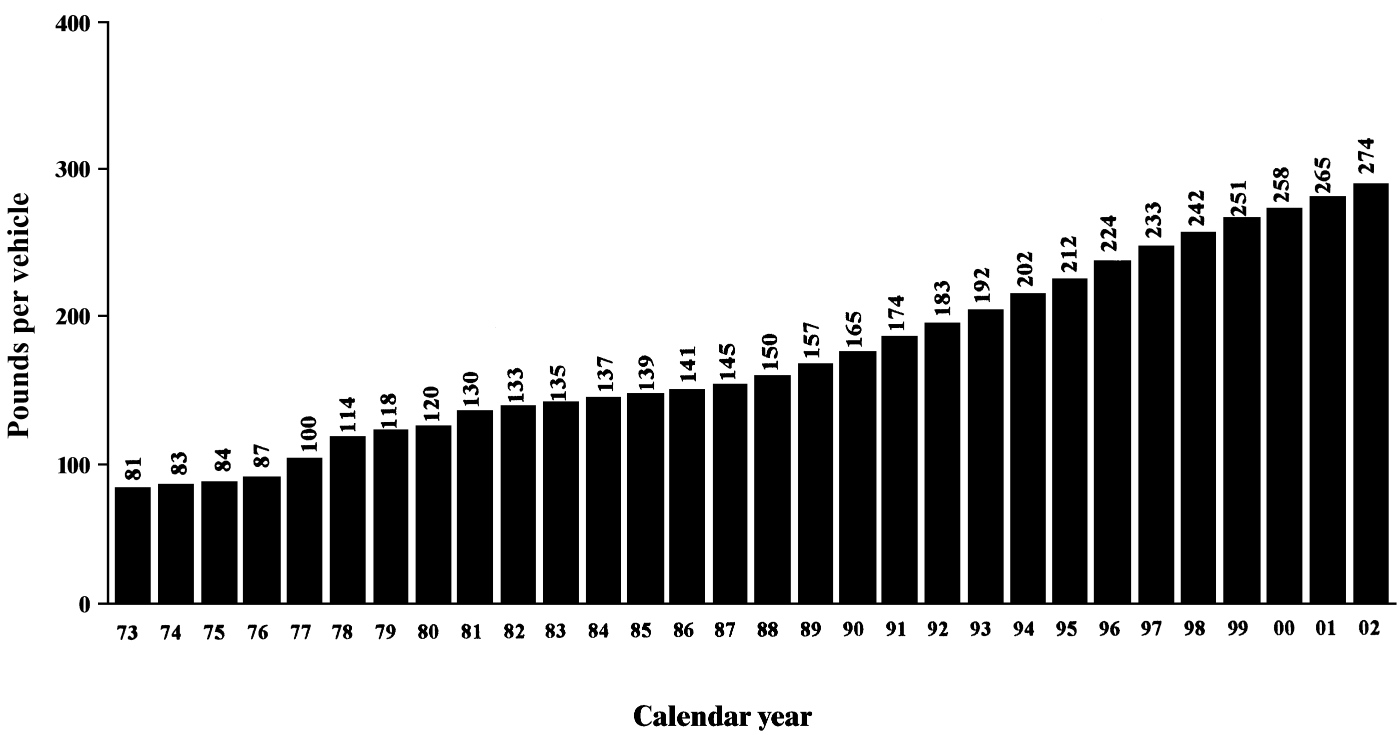

Fig. 1.6 North American light vehicle change in aluminum content, 1973 to 2002

facturing objectives, component performance criteria, and economic targets.

This reference volume is not intended as a guide to producing aluminum alloy castings; for example, it does not cover the details of how to design and build molds, inject the molten alloys, and sequence the finishing process. For more information on such matters, the reader is referred to the excellent aluminum casting industry publications of the American Foundry Society and similar organizations (Ref 1, 6–9) plus those of the Aluminum Association (Ref 10–12). For those interested in a broader overview of the entire aluminum industry, D.G. Altenpohl's volume (Ref 13) is recommended.

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DOI:10.1361/aacp2004p007

CHAPTER 2

Aluminum Casting Alloys

2.1 General

Aluminum casting alloy compositions parallel wrought alloy compositions in many respects. Hardening and desired properties are achieved through the addition of alloying elements and through heat treatment. Since work hardening plays no significant role in the development of casting properties, the use and purposes of some alloying elements differ in casting and wrought alloys.

The most important consideration in differentiating wrought and casting alloy compositions is castability. While wrought products are typically produced in simple round and rectangular cross sections by casting processes that minimize the depth and maximize the uniformity of the solidification front, solidification in engineered castings with complex shapes and variable rates of solidification present different demands on alloy solidification behavior. Cracking during and after solidification and internal shrinkage dictate alloys for shape casting that minimize these tendencies.

The term *castability* is not precisely defined. It is used to estimate the suitability of a composition for solidification in a specific process to produce defect-free, sound castings. For gravity casting, the components of castability are generally considered to be fluidity as the measure of mold-filling capability, resistance to hot cracking during and after solidification, and feeding characteristics that promote the flow of metal during solidification to avoid or minimize the formation of shrinkage voids. For pressure die castings, the criteria of castability are resistance to hot cracking, fluidity, die soldering and surface finish.

Fluidity is a complex function that can be quantified and mathematically defined. Fluidity is most strongly affected by temperature above the liquidus or degree of superheat. More fluid compositions at conventional pouring temperatures are those of eutectic or near-eutectic composition.

Improved feeding characteristics are usually associated with narrow solidus-liquidus ranges and in greater percent liquid at the eutectic temperature.

The tendency for solidification and postsolidification cracking is dominated by element effects on elevated-temperature strength and on solidification rate.

Die soldering is most strongly influenced by metal chemistry, but die condition and other process parameters are also important.

The most commonly used castability ratings were developed by consensus estimates based on practical experience. Castability ratings from A to F or from 1 to 10 imply excellent to poor casting characteristics, respectively. Castability and other fabricating and finishing ratings are summarized in Table 8.1 in Chapter 8.

The casting alloys used in the greatest volumes contain silicon in excess of that of most wrought alloys. Solidification results in shaped casting are improved by fluidity, elevated-temperature resistance to cracking, and feeding characteristics that sufficient amounts of silicon impart.

The optimal concentration of silicon depends in part on the casting process. Processes characterized by higher heat flux use alloys with higher silicon contents since fluidity is improved. Feeding, the compensation for internal shrinkage, also varies as a result of gradients in the solidification zone that are process controlled. In general, castability, is associated with alloys of reduced solidification range.

There are nevertheless many common foundry alloys that do not rely on silicon for casting performance.

The recyclability of aluminum is a principal material advantage, and a number of casting alloys have been developed specifically for production from remelted scrap. These "secondary" compositions specify broader impurity ranges and include additional elements as impurities to reflect variations in raw materials. By contrast, primary alloys that are produced from smelted aluminum, metallurgical metals, and master alloys display more restrictive and more limited, element-specific impurity limits.

2.2 Specifications

Aluminum castings are the subject of numerous specifications and standards. Within the United States, alloy chemistry and thermal practices are registered with the Aluminum Association (see Section 2.3.1 of this chapter). Procurement specifications and standards are developed and maintained by, among others, ASTM and Military and Federal agencies. Procedural methods and standards are often referenced. These pertain to radiographic and penetrant inspection, test procedures for determination of chemical, mechanical, and physical properties, and other required procedures. In many cases, specifications are written for specific parts or classes of parts by the purchaser. All specifications are subject to negotiation and exceptions to be agreed upon by the casting producer and the customer as part of the purchasing process.

Specifications for aluminum alloy chemistries include the effects of major, minor, and impurity elements:

- *Major alloying elements* define the ranges of elements that control castability and property development.
- *Minor alloying elements* control solidification behavior, modify eutectic structure, refine primary phases, refine grain size and form, promote or suppress phase formation, and reduce oxidation.
- *Impurity elements* influence castability and the form of insoluble phases that at times limit or promote desired properties.

Preferred major, minor, and impurity element concentrations and relationships may not be defined by alloy specifications. Optimal results are not implied by nominal chemistries. The addition of structure-controlling elements or combinations of elements can be contained within chemistry limits when not otherwise specified under "Other Elements Each."

Stoichiometric ratios for favored phase formation can be specified, but also may not be controlled or defined.

Concentration limits allow biasing of composition for castability and property development. For maximum strength, the concentration of elements that form hardening phases can be maximized. Improved ductility results from finer structures, restricting insoluble-element concentrations, and by controlling the concentrations of impurities in ratios that favor the formation of the least detrimental intermetallic constituents. Composition biasing can be specified in ingot procurement or can result from alloying adjustments in the foundry.

2.3 Alloy Designations

Designation systems and alloy nomenclature for aluminum casting alloys are not internationally standardized. Many nations have developed and published their own standards. Individual firms have also promoted alloys by proprietary designations. In North America, the most commonly used system is that developed and maintained by the Aluminum Association. General procurement specifications issued through government agencies and technical associations and societies typically reference this nomenclature.

2.3.1 The Aluminum Association (AA) Casting Alloy Designation System

The most widely used casting alloy designation system in the United States is the Aluminum Association (AA) alloy and temper systems (Ref 1), which are described below. Regrettably, the AA system is not universally used, and some of its earlier modifications are still widely quoted. Therefore, subsequent sections discuss the earlier variations as well as other rather widely used designations.

In the AA alloy designation, there are four numeric digits, with a period between the third and fourth. The meanings of the four digits are:

- *First digit:* Principal alloying constituent(s)
- *Second and third digits:* Specific alloy designation (number has no significance but is unique)
- *Fourth digit:* Casting (0) or ingot (1, 2) designation

Variations in the composition limits that are too small to require a change in numeric designation are indicated by a preceding letter (A, B, C, etc). The first version of an alloy, say 356.0, contains no letter prefix; the first variation has an A, e.g., A356.0, the second a B, for example, B356.0, and so forth.

The first digit defines the major alloying constituent or constituents, with the following categories being defined:

- lxx.x, pure aluminum (99.00% or greater)
- 2xx.x, aluminum-copper alloys
- 3xx.x, aluminum-silicon + copper and/or magnesium
- 4xx.x, aluminum-silicon
- 5xx.x, aluminum-magnesium
- 7xx.x, aluminum-zinc
- 8xx.x, aluminum-tin
- 9xx.x, aluminum + other elements
- 6xx.x, unused series

In designations of the 1xx.x type, the second and third digits indicate minimum aluminum content (99.00% or greater); these digits are the same as the two to the right of the decimal point in the minimum aluminum percentage expressed to the nearest 0.01%. For example, alloy 170.0 contains a minimum of 99.70% Al.

In 2xx.x through 8xx.x designations for aluminum alloys, the second and third digits have no numerical significance, but only arbitrarily identify individual alloys in the group.

In all casting alloy designations, the fourth digit, that to the right of the decimal point, indicates product form:

- 0 denotes castings
- 1 denotes standard ingot
- 2 denotes ingot having composition ranges narrower than but within those of standard ingot

Designations in the form xxx.1 and xxx.2 include the composition of specific alloys in remelt ingot form suitable for foundry use. Designations in the form xxx.0 in all cases define composition limits applicable to castings. Further variations in specified compositions are denoted by prefix letters used primarily to define differences in impurity limits. Accordingly, one of the most common gravity cast alloys, 356, has variations A356, B356, and C356; each of these alloys has identical major alloy contents, but has decreasing specification limits applicable to impurities, especially iron content.

Alloying-element and impurity limits for ingot are usually the same as those for castings of the same alloy. When the ingot is remelted, iron and silicon contents tend to increase and magnesium content decreases. For these reasons, ingot chemistry for some alloys may be somewhat different from those specified for castings.

Despite the broad acceptance of the AA casting alloy designation system, including recognition by the American National Standards Institute (ANSI), it remains relatively common to see the alloys listed with only the first three digits of the alloy designation, for example, for 356.0, one may see simply 356 (see Section 2.3.3 in this chapter). Technically, this is obsolete usage of the designation system, and for cast components the ".0" should always be utilized.

The nominal compositions and composition limits of aluminum alloys in commercial use today are presented in Table 2.1.

2.3.2 Aluminum Association Casting Temper Designation System

The Aluminum Association Casting Temper Designation System (Ref 1) uses letters and numbers to indicate the major types of thermal treatments applicable to engineered castings:

- F, as-cast
- O, annealed
- T4, solution treated and aged
- T5, precipitation hardened
- T6, solution heat treated, quenched, and precipitation hardened
- T7, solution heat treated, quenched, and overaged

Temper designation is presented immediately following the alloy designation. Thus, for a 356.0 alloy casting that has been solution heat treated, quenched, and artificially aged, the full alloy and temper designation would be shown as 356.0-T6. Examples of registered temper variations are A357.0-T61, 242.0-T571, and 355.0-T71.

Other variations of temper designations are permitted by the Aluminum Association Temper Designation System (Ref 1), the most common being the use of "P" added to a standard temper designation (e.g., T6P) indicating a producer variation of the standard processing treatment. There is further discussion of temper designations in Chapter 7, "Heat Treatment of Aluminum Castings."

2.3.3 Evolution of Designation System; Cross-Reference to Older Designations

As noted previously, over the years there have been several evolutionary steps in the development of the Aluminum Association casting alloy designation system, with the result that it is not uncommon to find variations of the current designations appearing on drawings and in publications from not too many years ago, and in some cases even in current publications. To assist in dealing with such variations, Table 2.2 illustrates a number of the variations in casting alloy designations over the past 50 years.

The overall most common variation is clearly the omission of the decimal point and the fourth digit, always a .0 for a foundry product. While inconsistent with current Aluminum Association standards, this variation is not usually a problem resulting in confusion, as for example it is relatively clear that an alloy designated 354 may safely be assumed to be 354.0 by today's standard system.

While the most common variation is the omission of the decimal point and the fourth digit in the designation, there are two other types of variations reflected in Table 2.2 that are also seen frequently and can be more confusing. One variation is simply a proprietary designation that has become rather widely known in the past, for example, Hiduminium, Frontier 40E, Precedent 71, and Almag 35. These designations originated before the alloy compositions were registered with the Aluminum Association and had no formal basis. They cause confusion because there is no obvious link to the current system if one does not have a conversion guide such as Table 2.2.

The other fairly often seen variation is the result of the significant revision of the Aluminum Association system in around 1990, when the guidelines for registering the alloys including copper and magnesium were changed. The result was that some alloys shifted classification; for example, alloy 195.0 became 295.0 and alloy 214.0 became 514.0.

2.3.4 The UNS Alloy Designation System

Another rather widely known alloy classification system is the Unified Numbering System (UNS) (Ref 2). The UNS system has the advantage of covering all metallic alloy systems.

For aluminum alloys, as illustrated in Table 2.2, this system is essentially an adaptation of the Aluminum Association alloy designation system to fit the UNS format. UNS numbers are obtained by taking the three digits to the left of the decimal point in the Aluminum Association system and adding A9 (meaning aluminum alloys) and a digit reflecting the letter prefix to the alloy designation. For alloys with no letter prefix, the next numeric digit after A9 is a 0; for those with A, the next digit is 1, for B, it is 2, and so forth.

Thus, in the UNS system, 356.0 becomes A90356, A356.0 becomes A91356, C356.0 becomes A93356; and so forth.

The UNS system is not as widely used for aluminum alloys as for certain other classes of alloys. An example would be copper alloys, for which the UNS designations have been selected as the U.S. standards.

2.3.5 International Casting Alloy Designations

Unlike the case for wrought aluminum alloys, there is no international accord on casting alloy designations, and other systems are rather universally used overseas (Ref 3). Most systems employ some system based on identifying the major alloying elements, but regrettably there are many variations of these.

One of the mostly widely used international systems is the Euronorm designation, and so, where applicable, designations of that type have been included in Table 2.2. There are no comparable Euronorm designations for about half of the alloys registered in the United States, nor is there any simple guide to generate them.

2.3.6 Nomenclature System for Aluminum Metal-Matrix Composites

Aluminum casting alloys are now regularly used as the matrix material in metal-matrix composites (MMC). The Aluminum Association, Inc, and ANSI H35.5 (Ref 4) have published a standard nomenclature system for such composites that builds on the standard casting alloy designation system as outlined below. Although this standard nomenclature has been established, some MMC suppliers have preferred their own designations. One reason is that matrix alloys may not coincide exactly with Aluminum Association ranges.

Table 2.1 Nominal composition and composition limits of aluminum alloy castings

Based on industry handbooks, notably *Aluminum Association Standards for Sand and Permanent Mold Castings*, and the *Aluminum Association Registration Sheets for Alloys in the Form of Castings and Ingot*

		Composition, wt%												
												Others		
Alloy	Type(a)	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Sn	Each(b)	Total(b)	Al
100.1	Nominal	...	0.7	...	...	...	...	...	...	...	...	...	...	...
	Limits	0.15	0.6–0.8	0.10	(c)	...	(c)	...	0.05	(c)	...	0.03	0.10	bal
150.1	Nominal	...	...	...	...	...	...	...	...	...	...	...	...	...
	Limits	(d)	(d)	0.05	(c)	...	(c)	...	0.05	(c)	...	0.03	0.10	bal
170.1	Nominal	...	...	...	...	...	...	...	...	...	...	...	...	...
	Limits	(e)	(e)	...	(c)	...	(c)	...	0.05	(c)	...	0.03	0.10	bal
201.0(f)	Nominal	...	...	...	...	...	...	...	...	...	...	...	...	...
	Limits	0.10	0.15	4.0–5.2	0.20–0.50	0.15–0.55	...	...	...	0.15–0.35	...	0.05	0.10	bal
203.0	Nominal	...	...	5.0	0.25	...	...	1.5	...	0.20	...	...	...	...
	Limits(g)	0.30	0.50	4.5–5.5	0.20–0.30	0.10	...	1.3–1.7	0.10	0.15–0.25	...	0.05	0.20	bal
204.0	Nominal	...	...	...	...	0.25	...	...	...	0.22	...	...	...	...
	Limits	0.20	0.35	4.2–5.0	0.10	0.15	...	0.05	0.10	0.15–0.30	0.05	0.05	0.15	bal
A206.0	Nominal	...	...	4.6	0.35	0.25	...	...	...	0.22	...	...	...	...
	Limits	0.05	0.10	4.2–5.0	0.20–0.50	0.15–0.35	...	0.05	0.10	0.15–0.30	0.05	0.05	0.15	bal
208.0(h)	Nominal	3.0	...	4.0	...	...	...	...	...	...	...	...	...	...
	Limits	2.5–3.5	1.2	3.5–4.5	0.50	0.10	...	0.35	1.0	0.25	...	...	0.50	bal
222.0(h)	Nominal	...	...	10.0	...	0.25	...	...	...	...	...	...	...	...
	Limits	2.0	1.5	9.2–10.7	0.50	0.15–0.35	...	0.50	0.8	0.25	...	...	0.35	bal
224.0(h)	Nominal	...	...	5.0	0.35	...	...	...	...	...	...	...	...	...
	Limits(i)	0.06	0.10	4.5–5.5	0.20–0.50	...	...	...	...	0.35	...	0.03	0.10	...
240.0	Nominal	...	...	8.0	0.5	6.0	...	0.5	...	...	...	...	...	...
	Limits	0.50	0.50	7.0–9.0	0.30–0.7	5.5–6.5	...	0.30–0.7	0.10	0.20	...	0.05	0.15	bal
242.0	Nominal	...	...	4.0	...	1.5	...	2.0	...	...	...	...	...	...
	Limits	0.7	1.0	3.5–4.5	0.35	1.2–1.8	0.25	1.7–2.3	0.35	0.25	...	0.05	0.15	bal
A242.0	Nominal	...	...	4.1	...	1.4	0.20	2.0	...	0.14	...	...	...	...
	Limits	0.6	0.8	3.7–4.5	0.10	1.2–1.7	0.15–0.25	1.8–2.3	0.10	0.07–0.20	...	0.05	0.15	bal
249.0(h)	Nominal	...	...	4.2	0.38	0.38	...	...	3.0	0.18	...	...	...	...
	Limits	0.05	0.10	3.8–4.6	0.25–0.50	0.25–0.50	...	...	2.5–3.5	0.02–0.35	...	0.03	0.10	bal
295.0	Nominal	1.1	...	4.5	...	...	...	...	...	...	...	...	...	...
	Limits	0.7–1.5	1.0	4.0–5.0	0.35	0.03	...	...	0.35	0.25	...	0.05	0.15	bal
308.0	Nominal	5.5	...	4.5	...	...	...	...	...	...	...	...	...	...
	Limits	5.0–6.0	1.0	4.0–5.0	0.50	0.10	...	...	1.0	0.25	...	...	0.50	bal
319.0	Nominal	6.0	...	3.5	...	...	...	...	...	...	...	...	...	...
	Limits	5.5–6.5	1.0	3.0–4.0	0.50	0.10	...	0.35	1.0	0.25	...	...	0.50	bal
328.0(h)	Nominal	8.0	...	1.5	0.40	0.40	...	...	...	...	...	...	...	...
	Limits	7.5–8.5	1.0	1.0–2.0	0.20–0.6	0.20–0.6	0.35	0.25	1.5	0.25	...	...	0.50	bal
332.0	Nominal	9.5	...	3.0	...	1.0	...	...	...	...	...	...	...	...
	Limits	8.5–10.5	1.2	2.0–4.0	0.50	0.50–1.5	...	0.50	1.0	0.25	...	...	0.50	bal
333.0	Nominal	9.0	...	3.5	...	0.28	...	...	...	...	...	...	...	...
	Limits	8.0–10.0	1.0	3.0–4.0	0.50	0.05–0.50	...	0.50	1.0	0.25	...	...	0.50	bal
336.0	Nominal	12.0	...	1.0	...	1.0	...	2.5	...	...	...	...	...	...
	Limits	11.0–13.0	1.2	0.50–1.5	0.35	0.7–1.3	...	2.0–3.0	0.35	0.25	...	0.05	...	bal
354.0	Nominal	9.0	...	1.8	...	0.5	...	...	...	...	...	...	...	...
	Limits	8.6–9.4	0.20	1.6–2.0	0.10	0.40–0.6	...	...	0.10	0.20	...	0.05	0.15	bal
355.0	Nominal	5.0	...	1.25	...	0.5	...	...	...	...	...	...	...	...
	Limits	4.5–5.5	0.6	1.0–1.5	0.50	0.40–0.6	0.25	...	0.35	0.25	...	0.05	0.15	bal
C355.0	Nominal	5.0	...	1.25	...	0.5	...	...	...	...	...	...	...	...
	Limits	4.5–5.5	0.20	1.0–1.5	0.10	0.40–0.6	...	...	0.10	0.20	...	0.05	0.15	bal
356.0	Nominal	7.0	...	...	...	0.32	...	...	...	...	...	...	...	...
	Limits	6.5–7.5	0.6	0.25	0.35	0.20–0.45	...	...	0.35	0.25	...	0.05	0.15	bal
A356.0	Nominal	7.0	...	...	...	0.35	...	...	...	...	...	...	...	...
	Limits	6.5–7.5	0.20	0.20	0.10	0.25–0.45	...	...	0.10	0.20	...	0.05	0.15	bal
357.0	Nominal	7.0	...	...	...	0.52	...	...	...	...	...	...	...	...
	Limits	6.5–7.5	0.15	0.05	0.03	0.45–0.6	...	...	0.05	0.20	...	0.05	0.15	bal
A357.0(j)	Nominal	7.0	...	...	...	0.55	...	...	...	0.12	...	...	...	...
	Limits	6.5–7.5	0.20	0.20	0.10	0.40–0.7	...	...	0.10	0.04–0.20	...	0.05	0.15	bal
D357.0(j)	Nominal	7.0	...	...	...	0.58	...	...	...	0.15	...	...	...	...
	Limits	6.5–7.5	0.20	...	0.10	0.55–0.6	...	...	...	0.10–0.20	...	0.05	0.15	bal
359.0	Nominal	9.0	...	...	...	0.6	...	...	...	...	...	...	...	...
	Limits	8.5–9.5	0.20	0.20	0.10	0.50–0.7	...	...	0.10	0.20	...	0.05	0.15	bal
360.0	Nominal	9.5	...	...	...	0.5	...	...	...	...	...	...	...	...
	Limits	9.0–10.0	2.0	0.6	0.35	0.40–0.6	...	0.50	0.50	...	0.15	...	0.25	bal
A360.0	Nominal	9.5	...	...	...	0.5	...	...	...	...	...	...	...	...
	Limits	9.0–10.0	1.3	0.6	0.35	0.40–0.6	...	0.50	0.50	...	0.15	...	0.25	bal

(continued)

(a) Both nominal compositions and composition limits are shown. Nominal values are midrange of limits for elements for which a composition range is specified. Limits are maximum unless a range is shown. (b) Maximum for "each" and "total" of elements not shown and present at 0.010% or more each, when expressed to the second decimal. (c) Ingot; 0.025% max Mn + Cr + Ti + V. (d) Ingot; 2.0 min Fe/Si ratio. (e) Ingot; 1.5 min Fe/Si ratio. (f) Also contains 0.40–1.0% (0.7% nominal) Ag. (g) Also contains 0.20–0.30% Sb (0.25% nominal), 0.20–0.30% Co (0.25% nominal), and 0.10–0.30% Zr, Ti + Zr contents = 0.50% max. (h) Alloy has been designated "Inactive" by the Aluminum Association, but still occurs in some publications. (i) Also contains 0.05–0.15 V and 0.10–0.25 Zr. (j) Also contains 0.04–0.07% (0.055% nominal) Be. (k) Also contains 0.03–0.015 (0.010% nominal) Sr and a maximum 0.001% P. (l) If iron exceeds 0.45%, manganese content shall not be less than one-half iron content. (m) Also contains 0.0003–0.007% (0.005% nominal) Be and 0.005% maximum B.

Table 2.1 (continued)

		Composition, wt%										Others		
Alloy	**Type(a)**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Ni**	**Zn**	**Ti**	**Sn**	**Each(b)**	**Total(b)**	**Al**
365.0	Nominal	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits(k)	9.5–11.5	0.15	0.03	0.50–0.8	0.10–0.50	. . .	. . .	0.07	0.04–0.15	0.03	0.03	0.10	bal
380.0	Nominal	8.5	. . .	3.5	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	7.5–9.5	2.0	3.0–4.0	0.50	0.10	. . .	0.50	3.0	. . .	0.35	. . .	0.50	bal
A380.0	Nominal	8.5	. . .	3.5	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	7.5–9.5	1.3	3.0–4.0	0.50	0.10	. . .	0.50	3.0	. . .	0.35	. . .	0.50	bal
383.0	Nominal	10.5	. . .	2.5	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	9.5–11.5	1.3	2.0–3.0	0.50	0.10	. . .	0.30	3.0	. . .	0.15	. . .	0.50	bal
384.0	Nominal	11.2	. . .	3.8	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	10.5–12.0	1.3	3.0–4.5	0.50	0.10	. . .	0.50	3.0	. . .	0.35	. . .	0.50	bal
B390.0	Nominal	17.0	. . .	4.5	. . .	0.55	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	16.0–18.0	1.3	4.0–5.0	0.50	0.45–0.65	. . .	0.10	1.5	0.20	. . .	0.10	0.20	bal
391.0	Nominal	19.0	. . .	. . .	. . .	0.58	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	18.0–20.0	1.2	0.20	0.30	0.45–0.7	. . .	. . .	0.10	0.20	. . .	0.10	0.20	bal
A391.0	Nominal	19.0	. . .	. . .	. . .	0.58	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits(l)	18.0–20.0	0.6	0.20	0.30	0.45–0.7	. . .	. . .	0.10	0.20	. . .	0.10	0.20	bal
B391.0	Nominal	19.0	. . .	. . .	. . .	0.58	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	18.0–20.0	0.15	0.20	0.30	0.45–0.7	. . .	. . .	0.10	0.20	. . .	0.10	0.20	bal
413.0	Nominal	12.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	11.0–13.0	2.0	1.0	0.35	0.10	. . .	0.50	0.50	. . .	0.15	. . .	0.25	bal
A413.0	Nominal	12.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	11.0–13.0	1.3	1.0	0.35	0.10	. . .	0.50	0.50	. . .	0.15	. . .	0.25	bal
443.0	Nominal	5.2	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	4.5–6.0	0.8	0.6	0.50	0.05	0.25	. . .	0.50	0.25	. . .	. . .	0.35	bal
B443.0	Nominal	5.2	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	4.5–6.0	0.8	0.15	0.35	0.05	. . .	. . .	0.35	0.25	. . .	0.05	0.15	bal
C443.0	Nominal	5.2	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	4.5–6.0	2.0	0.6	0.35	0.10	. . .	0.50	0.50	. . .	0.15	. . .	0.25	bal
A444.0	Nominal	7.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	6.5–7.5	0.20	0.10	0.10	0.05	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
512.0	Nominal	1.8	. . .	. . .	. . .	4.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	1.4–2.2	0.6	0.35	0.8	3.5–4.5	0.25	. . .	0.35	0.25	. . .	0.05	0.15	bal
513.0	Nominal	. . .	. . .	. . .	. . .	4.0	. . .	. . .	1.8	. . .	. . .	. . .	. . .	. . .
	Limits	0.30	0.40	0.10	0.30	3.5–4.5	. . .	. . .	1.4–2.2	0.20	. . .	0.05	0.15	bal
514.0	Nominal	. . .	. . .	. . .	. . .	4.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	0.35	0.50	0.15	0.35	3.5–4.5	. . .	. . .	0.15	0.25	. . .	0.05	0.15	bal
518.0	Nominal	. . .	. . .	. . .	. . .	8.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	0.35	1.8	0.25	0.35	7.5–8.5	. . .	0.15	0.15	. . .	0.15	. . .	0.25	bal
520.0	Nominal	. . .	. . .	. . .	. . .	10.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Limits	0.25	0.30	0.25	0.15	9.5–10.6	. . .	. . .	0.15	0.25	. . .	0.05	0.15	bal
535.0(m)	Nominal	. . .	. . .	. . .	0.18	6.8	. . .	. . .	. . .	0.18	. . .	. . .	. . .	. . .
	Limits	0.15	0.15	0.05	0.10–0.25	6.2–7.5	. . .	. . .	. . .	0.10–0.25	. . .	0.05	0.15	bal
705.0	Nominal	. . .	. . .	. . .	0.5	1.6	0.30	. . .	3.0	. . .	. . .	. . .	. . .	. . .
	Limits	0.20	0.8	0.20	0.40–0.6	1.4–1.8	0.20–0.40	. . .	2.7–3.3	0.25	. . .	0.05	0.15	bal
707.0	Nominal	. . .	. . .	. . .	0.50	2.1	0.30	. . .	4.2	. . .	. . .	. . .	. . .	. . .
	Limits	0.20	0.8	0.20	0.40–0.6	1.8–2.4	0.20–0.40	. . .	4.0–4.5	0.25	. . .	0.05	0.15	bal
710.0	Nominal	. . .	. . .	0.50	. . .	0.7	. . .	. . .	6.5	. . .	. . .	. . .	. . .	. . .
	Limits	0.15	0.50	0.35–0.65	0.05	0.6–0.8	. . .	. . .	6.0–7.0	0.25	. . .	0.05	0.15	bal
711.0	Nominal	. . .	1.0	0.50	. . .	0.35	. . .	. . .	6.5	. . .	. . .	. . .	. . .	. . .
	Limits	0.30	0.7–1.4	0.35–0.65	0.05	0.25–0.45	. . .	. . .	6.0–7.0	0.20	. . .	0.05	0.15	bal
712.0	Nominal	. . .	. . .	. . .	. . .	0.58	0.50	. . .	6.0	0.20	. . .	. . .	. . .	. . .
	Limits	0.30	0.50	0.25	0.10	0.50–0.65	0.40–0.6	. . .	5.0–6.5	0.15–0.25	. . .	0.05	0.20	bal
713.0	Nominal	. . .	. . .	0.7	. . .	0.35	. . .	. . .	7.5	. . .	. . .	. . .	. . .	. . .
	Limits	0.25	1.1	0.40–1.0	0.6	0.20–0.50	0.35	0.15	7.0–8.0	0.25	. . .	0.10	0.25	bal
771.0	Nominal	. . .	. . .	. . .	. . .	0.9	0.40	. . .	7.0	0.15	. . .	. . .	. . .	. . .
	Limits	0.15	0.15	0.10	0.10	0.8–1.0	0.06–0.20	. . .	6.5-7.5	0.10–0.20	. . .	0.05	0.15	bal
850.0	Nominal	. . .	. . .	1.0	. . .	. . .	. . .	1.0	. . .	. . .	6.2	. . .	. . .	. . .
	Limits	0.7	0.7	0.7–1.3	0.10	0.10	. . .	0.7–1.3	. . .	0.20	5.5–7.0	. . .	0.30	bal
851.0	Nominal	2.5	. . .	1.0	. . .	. . .	. . .	0.50	. . .	. . .	6.2	. . .	. . .	. . .
	Limits	2.0–3.0	0.7	0.7–1.3	0.10	0.10	. . .	0.30–0.7	. . .	0.20	5.5–7.0	. . .	0.30	bal
852.0	Nominal	. . .	. . .	2.0	. . .	0.75	. . .	1.2	. . .	. . .	6.2	. . .	. . .	. . .
	Limits	0.40	0.7	1.7–2.3	0.10	0.6–0.9	. . .	0.9–1.5	. . .	0.20	5.5–7.0	. . .	0.30	bal

(a) Both nominal compositions and composition limits are shown. Nominal values are midrange of limits for elements for which a composition range is specified. Limits are maximum unless a range is shown. (b) Maximum for "each" and "total" of elements not shown and present at 0.010% or more each, when expressed to the second decimal. (c) Ingot; 0.025% max Mn + Cr + Ti + V. (d) Ingot; 2.0 min Fe/Si ratio. (e) Ingot; 1.5 min Fe/Si ratio. (f) Also contains 0.40–1.0% (0.7% nominal) Ag. (g) Also contains 0.20–0.30% Sb (0.25% nominal), 0.20–0.30% Co (0.25% nominal), and 0.10–0.30% Zr, Ti + Zr contents = 0.50% max. (h) Alloy has been designated "Inactive" by the Aluminum Association, but still occurs in some publications. (i) Also contains 0.05–0.15 V and 0.10–0.25 Zr. (j) Also contains 0.04–0.07% (0.055% nominal) Be. (k) Also contains 0.03–0.015 (0.010% nominal) Sr and a maximum 0.001% P. (l) If iron exceeds 0.45%, manganese content shall not be less than one-half iron content. (m) Also contains 0.0003–0.007% (0.005% nominal) Be and 0.005% maximum B.

Table 2.2 Cross reference for older casting alloy designations and frequently used specifications

Current Aluminum Association designation	Former Aluminum Association designation	Former proprietary company names	Unified Numbering System (UNS) designation	Former Federal specification designation	Former ASTM specification designation	Former SAE specification designation	Former military specification designation	Current ISO specification designation	Current Euronorm specification designation
150.0	150	...	A01500	...	...	...	...	A1–99.5	...
201.0	201	K01	A02010	...	CQ51A	382	...	...	...
203.0	203	Hiduminium 350	A02030	...	...	...	...	...	...
204.0	204	A–U5GT	A02040	...	...	...	...	...	...
208.0	108	...	A02080	108	CS43A	...	...	...	...
213.0	C113	...	A02130	113	CS74A	33	...	...	...
222.0	122	...	A02130	122	CG100A	34	...	Al–Cu10Si2Mg	...
224.0	224	...	A02240	224	...	...	...	...	...
240.0	A140, A240	...	A02400	140	...	...	...	...	...
242.0	142	...	A02220	142	CN42A	39	4222	...	...
249.0	149	...	A02490	149	...	...	...	...	...
295.0	195	...	A02950	195	C4A	38	4231	...	...
296.0	B295	...	A02960	B195	...	380	...	...	...
308.0	A108	...	A03080	A108	...	...	...	Al–Si6Cu4	45000
319.0	319	Allcast	A03190	319	SC64D	326	...	Al–Si5Cu3	45200
328.0	328	Red X–8	A03280	...	SC82A	327	...	...	...
332.0	F332	...	A03320	F132	SC103A	332	...	Al–Si9Cu3Mg	...
333.0	333	...	A03330	333	...	...	...	...	...
336.0	A332	...	A03360	A132	SN122A	321	...	Al–Si12Cu	48000
354.0	354	...	A03540	...	...	...	C354	...	...
355.0	355	...	A03550	355	SC51A	322	4210	Al–Si5Cu1Mg	45300
C355.0	C355	...	A33550	C355	SC51B	355	C355	...	...
356.0	356	...	A03560	356	SG70A	323	356	...	...
A356.0	A356	...	A33560	A356	SG70B	336	A356	Al–Si7Mg	42000
357.0	357	...	A03570	357	...	...	4241	...	...
A357.0	A357	...	A33570	...	...	...	A357	...	...
358.0	B358	Tens–50	A03580	...	...	...	...	...	...
359.0	359	...	A03590	...	...	...	359	...	...
360.0	360	...	A03600	...	SG100B	...	...	...	...
A360.0	A360	...	A13600	...	SG100A	309	...	Al–Si10Mg	43100
365.0	...	Silafont–36	A03650	...	...	...	...	...	...
380.0	380	...	A03800	...	SC84B	308	...	...	...
A380	A380	...	A13800	...	SC84A	306	...	Al–Si8Cu3Fe	46500
383.0	383	...	A03830	...	SC102	383	...	...	...
384.0	384	...	A03840	...	SC114A	303	...	Al–Si10Cu2Fe	46100
A384.0	A384	...	A143840	...	...	...	...	...	...
390.0	390	...	A03080	...	SC174B	...	...	Al–Si17Cu4Mg	...
A390.0	...	...	A13900	...	...	...	...	...	...
B390.0	...	...	A23900	...	SC174B	...	...	...	...
391.0	...	Mercosil	A03910	...	...	...	...	...	...
A391.0	...	Mercosil	A13910	...	...	...	...	...	...
B391.0	...	Mercosil	A23910	...	...	...	...	...	...
393.0	393	Vanasil	A03930	...	...	...	...	...	...
413.0	13	...	A04130	...	...	...	...	...	...
A413.0	A13	...	A14130	...	...	305	...	Al–Si12Cu	44100
B443.0	43 (high purity)	...	A24430	43	S5A	...	...	...	...
C443.0	43	...	A34430	43	S5C	304	...	...	...
A444.0	A344	...	A14440	...	...	...	...	...	...
511.0	F514	...	A05110	F214	...	...	...	...	...
512.0	B514	...	A25120	B214	GS42A	...	...	...	...
513.0	A514	...	A05130	A214	GZ42A	...	...	...	...
514.0	214	...	A05140	214	G4A	320	...	Al–Mg5Si1	51300
518.0	218	...	A05180	...	...	...	...	...	...
520.0	220	...	A05200	220	G10A	324	4240	...	...
535.0	535	Almag 35	A05350	Almag 35	GM70B	...	4238	...	...
A535.0	A218	...	A15350	A218	...	...	...	...	...
705.0	603	Ternalloy 5	A07050	Ternalloy 5	ZG32A	311	...	...	...
707.0	607	Ternalloy 7	A07070	Ternalloy 7	ZG42A	312	...	...	...
710.0	A712	...	A07100	A612	ZG61B	313	...	...	...
711.0	C712	...	A07110	...	ZC60A	314	...	...	...
712.0	D712	Frontier 40E	A07120	40E	ZG61A	310	...	Al–Zn5Mg	71000
A712.0	A712	...	A17120	...	...	...	...	...	...
C712.0	C612	...	...	...	...	...	...	...	...
713.0	613	Tenzaloy	A07130	Tenzaloy	ZC81A	315	...	...	...
771.0	...	Precedent 71A	A07710	Precedent 71A	...	...	...	...	...
772.0	B771	Precedent 71B	A07720	Precedent 71B	...	...	...	...	...
850.0	750	...	A08500	750	...	...	...	...	...
851.0	A850	...	A08510	A750	...	...	...	...	...
852.0	B850	...	A08520	B750	...	...	...	...	...

The designation system for aluminum metal-matrix composites consists of four parts:

- The matrix alloy designation employs the Aluminum Association alloy designation as described in Section 2.1 in this chapter. It is immediately followed by a slash that separates it from the rest of the composite designation.
- The composition of the reinforcement is shown immediately after the slash, using the appropriate chemical designation, with the exception that no subscripts or superscripts are used. Some common examples cited in the standard are: C for graphite, SiC for silicon carbide, and Al2O3 for aluminum oxide (alumina). This reinforcement designation is also followed without space by a slash.
- The volume percent of the reinforcement is shown immediately after the second slash. It is always presented as two digits, for example, 05 for 5%, 10 for 10%, 20 for 20%, and so forth.
- Immediately following the percentage is a single lower-case letter for the type of reinforcement: c for cut or chopped fibers, filaments, or monofilaments; f for continuous fibers, filaments, or monofilaments; p for particles (particulate); and w for whiskers.

Some common illustrations of cast aluminum metal-matrix composite designations are:

- A356.0/Al2O3/05f: Alloy A356.0 reinforced with 5% aluminum filaments
- 360.0/C/20c: Alloy 360.0 reinforced with 20% chopped fibers
- 380.0/SiC/10p: Alloy 380.0 reinforcement 10% silicon carbide particulate

2.4 Composition Groupings

Although a large number of aluminum casting alloys have been developed, there are seven basic families:

- Aluminum-copper (2xx)
- Aluminum-silicon-copper (3xx)
- Aluminum-silicon (4xx)
- Aluminum-silicon-magnesium (3xx)
- Aluminum-magnesium (5xx)
- Aluminum-zinc-magnesium (7xx)
- Aluminum-tin (8xx)

2.4.1 Aluminum-Copper

Aluminum-copper alloys have been used extensively in cast and wrought form where strength and toughness are required. These alloys exhibit high strength and hardness at room and elevated temperatures.

The first significant aluminum casting alloys contained copper at concentrations up to 10%. With no understanding of heat treatment, these alloys displayed significantly improved strengths and hardnesses in the as-cast state.

Many alloys containing 4 to 5% Cu have been developed, usually with varying amounts of magnesium. Silver accelerates aging response and reduces the risk of stress corrosion. These heat treatable compositions represent the highest-strength capabilities of any commercial casting alloys. With controlled impurities, excellent ductilities are also achieved. The combination of tensile properties and ductility provide exceptional toughness.

Alloys of this type are susceptible to solidification cracking and to interdendritic shrinkage. Exacting foundry techniques are required to avoid these conditions. In permanent mold or other rigid mold casting methods, excellent grain refinement and selective chilling are essential.

Copper-containing aluminum alloys are less resistant to corrosion, and certain compositions and material conditions may be susceptible to stress corrosion.

Copper is typically the alloy basis for improved mechanical properties at elevated temperature, often with nickel additions.

2.4.2 Aluminum-Silicon-Copper

Among the most widely used aluminum casting alloys are those that contain silicon and copper. The amounts of both additions vary widely, so that copper predominates in some alloys and silicon in others. Copper contributes to strengthening and machinability, and silicon improves castability and reduces hot shortness. Alloys containing higher hypoeutectic concentrations of silicon are normally better suited for more complex castings and for permanent mold and die casting processes.

Aluminum-silicon-copper alloys with less than 5.6% Cu are heat treatable, but the more important alloys of this family are those also containing magnesium. Heat treatment response is enhanced, leading to a very attractive range of properties including premium-strength capabilities.

Many hypereutectic silicon alloys (12 to 30% Si) also contain copper. The primary silicon phase imparts excellent wear resistance, and copper contributes to matrix hardening and elevated-temperature strength.

2.4.3 Aluminum-Silicon

Binary aluminum-silicon alloys exhibit excellent fluidity, castability, and corrosion resistance. These alloys display low strength and poor machinability. Ductility, which can be exceptional, is a function of low impurity concentrations and microstructural features. The strength, ductility, and castability of hypoeutectic aluminum-silicon alloys can be further improved by modification of the aluminum-silicon eutectic. Modification is particularly advantageous in sand castings and can be effectively achieved through the controlled addition of sodium and/or strontium. Calcium is a weak eutectic modifier and a more lamellar eutectic can be achieved with antimony. Higher solidification rates also promote a finer unmodified eutectic microstructure.

Aluminum-silicon alloys exhibit low specific gravity and coefficients of thermal expansion.

In hypereutectic aluminum-silicon alloys, refinement of the proeutectic silicon phase by phosphorus additions is essential for casting and product performance.

2.4.4 Aluminum-Silicon-Magnesium

The addition of magnesium to aluminum-silicon alloys forms the basis for an extremely important and useful family of compositions that combines outstanding casting characteristics with excellent properties after heat treatment. Corrosion resistance is also excellent, and a low level of thermal expansion is retained.

While not as strong as high-strength Al-Cu and Al-Si-Cu alloys, the mechanical properties of several Al-Si-Mg alloys provide mechanical properties in the premium-strength range. Beryllium additions improve strength and ductility by affecting the morphology and chemistry of the iron-containing intermetallic.

Eutectic modification remains important as a means of improving strength, substantially increasing elongation, and improving casting results.

2.4.5 Aluminum-Magnesium

These are essentially single-phase binary alloys with moderate to high strength and toughness. Their most important characteristic is corrosion resistance, including exposure to seawater and marine atmospheres. This characteristic is also the basis for extensive use in food and beverage processing. Aluminum-magnesium alloys offer excellent weldability and are often used in architectural and other decorative applications. Aluminum-magnesium alloys have good machinability, weldability, and an attractive appearance whether as-cast, machined, polished, or anodized.

In comparison with aluminum-silicon alloys, all aluminum-magnesium alloys require more care in gating, larger risers, and greater control of temperature gradients.

Magnesium in aluminum alloys increases oxidation rates. In the molten state, magnesium losses can be significant and oxides of aluminum and magnesium can affect casting quality. Spinels of aluminum and magnesium oxides form with unprotected exposure at high molten metal temperatures. The potential for inclusions is especially important because many applications involve polishing and/or fine surface finishing.

Alloys containing >7.0% Mg are heat treatable, although thermal treatments are more typically used to stabilize properties that could otherwise change, in some compositions, over long periods of time.

2.4.6 Aluminum-Zinc-Magnesium

Many alloys of this type naturally age, achieving full strength within 20 to 30 days at room temperature after casting. Solution heat treatment is not typically necessary for property development. Rapid solidification in these alloys can result in microsegregation of magnesium-zinc phases that reduces hardening potential. Conventional solution heat treatments can be used when adequate property development does not occur through natural aging.

Since high-temperature solution heat treatment and quench are not normally required, the cost of heat treatment, high residual stress levels and distortion are avoided.

Artificial aging treatments can be used to accelerate the hardening process, and annealing treatments accomplish the same purpose with improved dimensional and structural stability.

These alloys typically display moderate to good tensile properties in the as-cast condition. The melting temperatures of alloys of this group are high, an advantage in castings that are to be brazed. Machinability and resistance to general corrosion is usually good. The chemistry of most alloys is controlled to minimize stress-corrosion susceptibility.

The castability of Al-Zn-Mg alloys is poor, and good foundry practices are required to minimize hot tearing and shrinkage defects.

2.4.7 Aluminum-Tin

Tin is the major alloying element in compositions developed for bearing applications. It has also been employed with bismuth, lead, and cadmium at lower concentrations to provide free-machining properties. The 850-series alloys can often be substituted for 660 or similar bronzes. Their light weight minimizes loads in reciprocating applications, and heat dissipation improves bearing life.

Alloys containing 5.0 to 7.0% Sn are broadly used in bearings and bushings in which low friction, compressive strength, fatigue strength, and resistance to corrosion are important criteria. Additions of copper, nickel, and magnesium contribute to hardness and strength, and silicon is added to improve castability, reduce hot shortness, and increase compressive yield strength.

Most bearings are produced by the permanent mold process. Higher-solidification rates promote the finer, more uniform dispersion of tin. Larger, special-design, and low-volume bearings are nevertheless cast successfully in sand molds. Because most bearings are simple hollow or solid cylinders, the direct chill (DC) casting process has also been used for production.

Aluminum-tin alloys are unique among significant compositions. Aluminum and tin are essentially immiscible. Before and after solidification, tin is present in dispersed form. Mechanical agitation is required initially to achieve suspension of tin, and, because of density differences, gravity segregation may occur over time in the molten state.

Aluminum-tin alloys containing copper are conventionally precipitation hardened and may be fully heat treated. Because most bearings are cast in simple solid or hollow cylindrical shapes, parts may be plastically cold worked to improve compressive yield strength. Solidification and thermal stresses are also relieved by axial compression resulting in 4% permanent deformation.

2.5 Effects of Alloying Elements

2.5.1 Antimony

At concentration levels equal to or greater than ~0.10%, antimony refines the aluminum-silicon eutectic. The effect is essentially that of modification, but a distinctly lamellar eutectic rather than a fine fibrous form results. The effectiveness of antimony in altering the eutectic structure depends on an absence of phosphorus and on an adequately rapid rate of solidification. Antimony also reacts with either sodium or strontium to form coarse intermetallics with adverse effects on castability and metallurgical structure.

Antimony is classified as a heavy metal with potential toxicity and hygiene implications, especially associated with stibine gas (SbH_3) formation and the effects of human exposure to other antimony compounds.

2.5.2 Beryllium

Additions of a few parts per million beryllium can be effective in reducing oxidation losses and associated inclusions in magnesium-containing compositions.

At higher concentrations (>0.04%), beryllium affects the form and composition of iron-containing intermetallics, markedly improving strength and ductility. In addition to changing the morphology of the insoluble phase from script or plate to nodular form, beryllium changes its composition, rejecting magnesium from the Al-Fe-Si complex and thus permitting its full use for hardening purposes.

Beryllium-containing compounds are, however, known carcinogens that require specific precautions in melting, molten metal handling, dross handling, dross disposition, and welding.

2.5.3 Bismuth

Bismuth additions improve the machinability of cast aluminum alloys at concentrations greater than 0.1%.

2.5.4 Boron

Boron combines with other metals to form borides, such as AlB_2 and TiB_2. Titanium boride forms stable nucleation sites that interact with active grain-refining phases such as $TiAl_3$ for grain refinement.

Metallic borides reduce tool life in machining operations and form coarse or agglomerated inclusions with detrimental effects on mechanical properties and ductility. Borides also contribute to sludging, the precipitation of intermetallics from liquid solution in furnaces and troughing.

Boron treatment of aluminum-containing peritectic elements such as titanium, zirconium, and vanadium is practiced to improve purity and conductivity in electrical applications. Rotor alloys may specify boron to exceed titanium and vanadium contents to ensure either the complexing or precipitation of these elements for improved electrical performance.

2.5.5 Cadmium

In concentrations exceeding 0.1%, cadmium improves machinability. Precautions that acknowledge volatilization of cadmium at 1413 ºF (767 ºC) are essential.

2.5.6 Calcium

Calcium is a weak aluminum-silicon eutectic modifier. It increases hydrogen solubility and is often responsible for casting porosity at trace concentration levels. Calcium greater than approximately 0.005% also adversely affects ductility in aluminum-magnesium alloys.

2.5.7 Chromium

Additions of chromium are commonly made in low concentrations to room-temperature aging and thermally unstable compositions in which germination and grain growth are known to occur. Chromium typically forms the compound $CrAl_7$, which displays extremely limited solid-state solubility and is therefore useful in suppressing grain-growth tendencies. Sludge that contains iron, manganese, and chromium is sometimes encountered in die casting compositions, but it is rarely encountered in gravity casting alloys. Chromium improves corrosion resistance in certain alloys and increases quench sensitivity at higher concentrations.

2.5.8 Copper

Copper substantially improves strength and hardness in the as-cast and heat treated conditions. Alloys containing 4 to 5.5% Cu respond most strongly to thermal treatment and display relatively improved casting properties. Copper generally reduces resistance to general corrosion and in specific compositions and material conditions increases stress-corrosion susceptibility. Conversely, low concentrations of copper in aluminum-zinc alloys inhibit stress corrosion.

Copper reduces hot tear resistance and increases the potential for interdendritic shrinkage.

2.5.9 Iron

Iron improves hot-tear resistance and decreases the tendency for die sticking or soldering in die casting. Increases in iron content are accompanied by substantially decreased ductility. Iron reacts to form a number of intermetallic phases, the most common of which are $FeAl_3$, $FeMnAl_6$, and $\alpha AlFeSi$. These essentially insoluble phases are responsible for improvements in strength, especially at elevated temperature, but also the embrittlement of the microstructure. As the fraction of insoluble phases increases with increased iron content, casting considerations such as feeding characteristics are adversely affected. Iron participates in the formation of sludging phases with manganese, chromium, and other elements.

2.5.10 Lead

Lead is used at concentrations greater than 0.1% to improve machinability.

2.5.11 Magnesium

Magnesium is the basis for strength and hardness development in heat treated aluminum-silicon alloys and is commonly used in more complex aluminum-silicon alloys containing copper, nickel, and other elements for the same purpose. The hardening-phase Mg_2Si displays a useful solubility limit corresponding to approximately 0.70% Mg, beyond which either no further strengthening occurs or matrix softening takes place. Common high-strength aluminum-silicon compositions specify magnesium in the range of 0.40 to 0.070%.

Binary aluminum-magnesium alloys are widely used in applications requiring a bright surface finish, excellent response to chemical finishing, corrosion resistance, and attractive combinations of strength and ductility. Common compositions range from 4 to 10% Mg, and compositions containing more than 7% Mg are heat treatable. Instability and long-term room-temperature aging at higher magnesium concentrations can be avoided by heat treatment.

2.5.12 Manganese

Normally considered an impurity in casting compositions, manganese is controlled to low levels in most gravity cast compositions. Manganese is an important element in work-hardened

wrought alloys through which secondary foundry compositions may contain higher manganese levels. In the absence of work hardening, manganese offers no significant benefits in cast aluminum alloys. Some evidence exists, however, that a high-volume fraction of $MnAl_6$ in alloys containing more than 0.5% Mn may beneficially influence internal soundness (Ref 5). Manganese can also be employed to alter response in chemical finishing and anodizing. Iron and manganese may be considered isomorphous, and alloy chemistry may reflect stoichiometries favoring the least detrimental insoluble Al-Fe-Mn phases.

2.5.13 Mercury

Compositions containing mercury were developed as sacrificial anodes for cathodic protection systems, especially in marine environments. The use of these optimally electronegative alloys, which do not passivate in seawater, was severely restricted for environmental reasons.

2.5.14 Nickel

Nickel is commonly used with copper to enhance elevated-temperature properties. It also reduces coefficient of thermal expansion.

2.5.15 Phosphorus

As AlP_3, phosphorus nucleates and refines primary silicon-phase formation in hypereutectic aluminum-silicon alloys. At parts per million concentrations, phosphorus coarsens the eutectic structure in hypoeutectic aluminum-silicon alloys and diminishes the effectiveness of common eutectic modifiers, sodium and strontium.

2.5.16 Silicon

The outstanding effect of silicon in aluminum alloys is the improvement of casting characteristics. Additions of silicon dramatically improve fluidity, hot tear resistance, and feeding characteristics. The most prominently used compositions in all aluminum casting processes are those in which silicon plays a major role. Commercial alloys span the hypoeutectic and hypereutectic ranges up to about 30% Si.

Increasing silicon content improves fluidity for filling thin walls and for reproducing more intricate designs and details. Aluminum-silicon alloys are typically more resistant to solidification cracking and display excellent castability and feeding characteristics.

Percent liquid in the solidification range is dictated by the initial composition and by the degree of nonequilibrium cooling. For higher-solidification-rate processes such as pressure die and permanent mold casting and for thinner sections in which more rapid solidification takes place, shrinkage porosity is strongly affected by the temperature at which mass feeding from liquid to partially solidified structures no longer occurs. Feeding to minimize shrinkage porosity improves as the volume fraction solidified is increased at the temperature at which mass feeding ceases. For this reason, the most desirable silicon content of aluminum-silicon alloys corresponds to the characteristic process solidification rate. For slow cooling rate processes such as plaster, investment, and sand, the preferred range is 5 to 7%, for permanent mold 7 to 9%, and for die casting 8 to 12%. The bases for these recommendations are the relationship between cooling rate and fluidity and the effect of percentage of eutectic on feeding as solidification progresses.

Silicon combines with magnesium to form Mg_2Si in heat treatable alloys. It combines with iron and other elements to form complex insoluble phases.

Silicon also reduces specific gravity and coefficient of thermal expansion.

2.5.17 Silver

Used in only a limited range of aluminum-copper premium-strength alloys at concentrations of 0.5 to 1.0%. Silver contributes to precipitation hardening and stress-corrosion resistance.

2.5.18 Sodium

Sodium modifies the aluminum-silicon eutectic. In the absence of phosphorus, recovered concentrations of 0.01% are effective. Sodium interacts with phosphorus to reduce its effectiveness in modifying the eutectic and that of phosphorus in the refinement of the primary silicon phase.

Sodium at less than 0.005% is embrittling in aluminum-magnesium alloys.

Sodium is rapidly lost in molten aluminum through its high vapor pressure so that modifying effects are transient. Periodic additions are required to maintain modification levels.

Sodium increases surface tension and through addition methods can increase hydrogen content. Overmodification increases misrun tendencies in gravity casting.

Unlike some other modifiers, sodium provides effective aluminum-silicon eutectic modification under all solidification conditions.

2.5.19 Strontium

Strontium modifies the aluminum-silicon eutectic. Effective modification can be achieved at very low addition levels, but a range of recovered strontium of 0.008 to 0.04% is commonly used. Lower concentrations are effective with higher solidification rates. Higher addition levels are associated with casting porosity. Degassing efficiency may also be adversely affected at higher strontium levels.

Strontium has been regarded as ineffective as a modifier at slow solidification rates, but some investigators report beneficial effects in AFS Level 4 and 5 structures in 319.0 and 356.0 alloys when >200 ppm Sr is present.

2.5.20 Tin

Tin is effective in improving antifriction characteristics and is therefore useful in bearing applications. Casting alloys may contain up to 25% Sn. Additions of tin also improve machinability.

2.5.21 Titanium

Titanium is extensively used to refine the grain structure of aluminum casting alloys, often in combination with smaller amounts of boron. The operable phase is $TiAl_3$ with lattice spacing closely matched to that of aluminum. Titanium in excess of the

stoichiometry of TiB_2 is necessary for effective grain refinement. Titanium is often employed at concentrations greater than those required for grain refinement to reduce cracking tendencies in hot-short compositions.

2.5.22 Zinc

Zinc offers no significant benefits in aluminum casting. Accompanied by the addition of copper and/or magnesium, however, zinc results in attractive heat treatable or naturally aging compositions. A number of such compositions are in common use. Zinc is also commonly found in secondary gravity and die casting compositions. In these alloys, tolerance for up to 3% Zn allows the use of lower-grade and wrought alloy scrap.

2.6 Alloy Groupings by Application or Major Characteristic

2.6.1 General-Purpose Alloys

Alloys with silicon as the major alloying constituent are the most important commercial casting alloys, primarily because of their superior casting characteristics. The large number of alloys of this type that have been developed displays a broad range of properties.

Binary aluminum-silicon alloys (443.0, 444.0, 413.0, and A413.0) are low-density, weldable, and resistant to corrosion. Although castings of these alloys are somewhat difficult to machine, good results are obtained with cutting fluids, sintered carbide tools, and chip breakers.

Alloy 443.0 is used with all casting processes for parts in which strength is less important than ductility, resistance to corrosion, and pressure tightness.

Permanent mold alloys 444.0 and A444.0 display high ductility and are used where impact resistance is a primary consideration.

Alloys 413.0 and A413.0 are close to the eutectic composition and, as a result, have very high fluidity. They are useful in die casting and where large-area, thin-walled parts with cast-in lettering or other high-definition details are required.

Representative applications for these alloys are:

- Architectural panels and spandrels
- Outdoor lamp housings
- Lawn mower decks
- Outdoor grills
- Marine components
- Cooking utensils
- Parts used in food, dairy, and beverage processing
- Medical and dental equipment
- Electronic cabinet frames and components
- Tire molds
- Escalator and moving sidewalk tread plates and parts
- Highway railing posts (Fig. 2.1); alloy A444.0 being the standard for this application

Aluminum-silicon-copper alloys such as 308.0, 319.0, 360.0, 380.0, and 384.0 offer good casting characteristics, higher strength and hardness, and improved machinability with reduced ductility and lower resistance to corrosion. These and similar general-purpose alloys are often produced in the as-cast condition. Artificial aging can improve hardness, stability, and machinability. Typical applications include:

- Machinery
- Transmission cases (Fig. 2.2)
- Engine blocks
- Gas meters and regulators
- Gear blocks
- Gear cases
- Fuel pumps
- Impellers
- Instrument cases
- Lawnmower decks
- Intake manifolds
- Cylinder heads
- Clutch housings
- Oil pans
- Outboard motor propellers, motor parts and housings

Fig. 2.1 Example of one of the many highway railing post designs utilizing aluminum castings that have been developed. The alloy is A444.0-T4 with minimum elongation in permanent mold castings of 20% in front flanges for maximum energy absorption during impact.

Aluminum-silicon-magnesium alloys including 356.0 and A356.0 have excellent casting characteristics and resistance to corrosion. Heat treatment provides combinations of tensile and physical properties that make them attractive for many applications including machinery, automotive, military, and aerospace parts. Higher tensile properties are obtained with 357.0, A357.0, 358.0, and 359.0 alloys. The high properties of these alloys, attained by heat treatment to the fully hardened condition, are of special interest in structural applications. Developments in high-integrity die casting have resulted in low-iron, manganese-containing Al-Si-Mg alloys such as 365.0 and AlMg3Mn. Some typical uses include:

- Automotive space frames
- Automotive wheels
- Truck wheels
- Axle and differential housings (Fig. 2.3)
- Pump bodies
- Meter bodies
- Compressor bodies
- Intake manifolds
- Cylinder heads
- Dies for plastic injection molding
- Machine parts
- Truck and bus frames and chassis components
- Suspension saddles (Fig. 2.4)
- Aircraft pylons, canopies, flaps, speed-brakes hatch covers, and other fittings
- Impellers
- Wave guides
- Electronic cases
- Fuel pumps
- Missile bodies, fins, and other structural parts
- Industrial beam heads
- Brake cylinders
- Automobile cross members and suspension components

Aluminum-silicon-copper-magnesium alloys such as 328.0. 333.0, 354.0, 355.0, and C355.0 offer excellent strength and hardness with some sacrifice in ductility and corrosion resistance. Casting characteristics are good, but inferior to those displayed by copper-free aluminum-silicon alloys. Properties in the as-cast condition can be acceptable for some applications, but these alloys are typically heat treated for optimal properties. Alloy C355.0 with low iron is a higher-strength version of 355.0. When premium-strength casting processes are used, even higher tensile properties can be obtained with heat treated Alloy 354.0. Alloys of this type are routinely cast in sand and permanent mold.

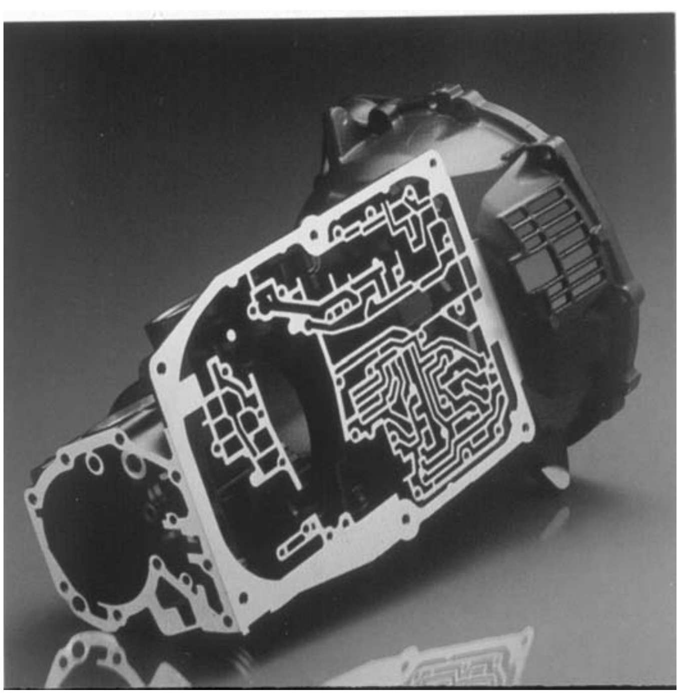

Fig. 2.2 Die cast alloy 380.0 transmission case

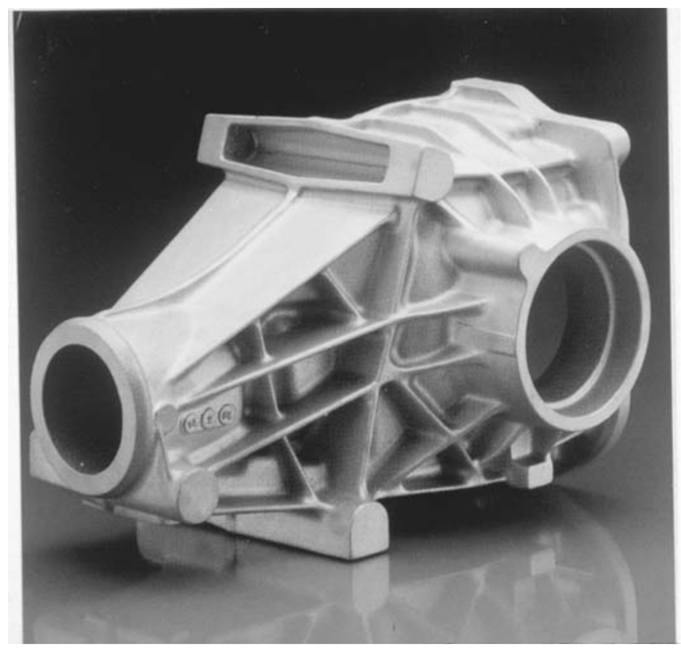

Fig. 2.3 Die cast alloy 380.0 rear axle housing

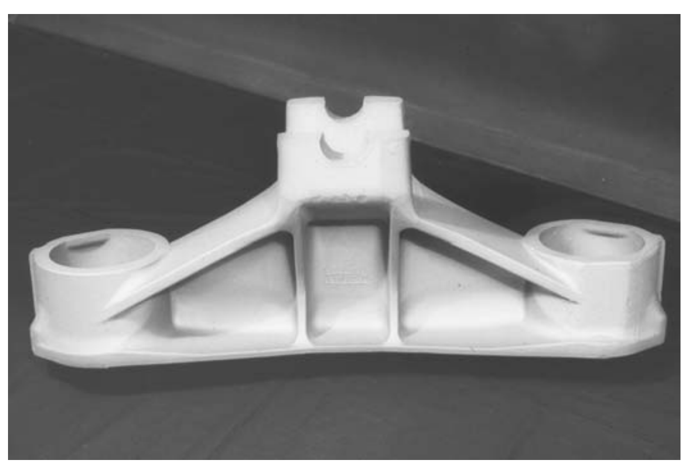

Fig. 2.4 Alloy A356.0 trailer suspension saddle

Applications include:

- Engine cooling fans
- Clutch housings
- Crankcases
- High-speed rotating parts such as fans and impellers
- Structural aerospace components
- Air compressor pistons
- Fuel pumps (Fig. 2.5)
- Compressor cases
- Rocker arms
- Timing gears
- Machine parts

2.6.2 Elevated-Temperature Alloys

Many aluminum alloys have been developed to provide strength, wear resistance, and hardness at elevated temperatures. The retention of these properties as temperature increases is an advantage in many applications.

Cast aluminum alloy pistons featuring low specific gravity, low thermal expansion, elevated-temperature strength, wear resistance, and high thermal conductivity are the international standard for internal combustion engines. Lower inertial forces permit higher engine speeds, reduced bearing requirements, and lighter, simpler crankshaft designs.

Aluminum pistons are usually permanent mold castings. Wrist pin bore struts and compression ring-groove inserts can be cast-in; in large diesel engine pistons, integral cooling passages can be incorporated through copper coils or coring methods.

The alloy most commonly used for pistons in passenger cars, sports-utility vehicles, and light trucks, 332.0-T5, demonstrates a desirable combination of foundry, mechanical, and physical characteristics, including low thermal expansion. Precipitation hardening from air or water quenching from the mold improves hardness for improved machinability and eliminates or reduces changes in dimensions from residual growth at operating temperatures.

Fig. 2.5 Alloy C355.0 fuel pump housing

More complex aluminum-silicon alloys have been developed to meet the demands of high specific output, fuel-efficient engines that operate at higher temperatures. Some of these alloys retain yield strengths over 10 ksi (70 MPa) at temperatures exceeding 500 °F (260 °C).

Piston alloys for heavy-duty and diesel engines include low-expansion alloys 332.0-T5 and 336.0-T551. Alloy 242.0-T571 offers higher thermal conductivity and superior properties at elevated temperatures.

Other applications of aluminum alloys for elevated-temperature use include air-cooled cylinder heads for aircraft and motorcycles. Alloy 220.0-T61 was once used extensively for this purpose, but has been largely replaced by more castable 242.0 and 243.0 alloys with superior elevated-temperature properties.

Alloys 295.0, 355.0, and C355.0 have been extensively used in applications requiring strength and hardness at temperatures up to 350 °F (175 °C). They include aircraft motor and gear housings. Alloy A201.0 and 204.0/206.0 type alloys have also been used in this temperature range when the combination of high strength at room temperatures and elevated temperatures is required.

Applications include:

- Cylinder heads
- Motorcycle engine parts
- Gear housings
- Pistons
- Structural parts exposed to elevated temperatures

2.6.3 Wear Resistant Alloys

Alloys containing greater-than-eutectic silicon concentrations display low specific gravity and elevated-temperature strength and are often used in applications requiring a high degree of wear resistance. While wear resistance is usually associated with surface hardness resulting from matrix properties or anodized coatings, wear resistance in these alloys results from the presence of a large volume fraction of hard primary silicon particles in the microstructure. Growth in the popularity of these alloys has accelerated in recent years. Alloys include 390.0, 392.0, and 393.0.

Hypereutectic aluminum-silicon alloys are relatively more difficult to cast and machine, but are used in all casting processes.

Matrix-hardening alloys also provide improved wear resistance. Alloys of the 2xx.0 and 355.0 family are considered wear resistant.

Applications include:

- Brake rotors
- Cylinder blocks
- Cylinder liners
- Marine engines
- Pistons

2.6.4 Moderate-Strength Alloys with Low Residual Stresses

A number of casting compositions have been developed to provide strength and hardness without heat treatment through natural aging. These alloys offer dimensional stability that reduces distortion during machining and simplifies straightening to close tol-

erances. The cost of heat treatment is avoided or reduced and postweld heat treatment is typically not required.

In many cases, properties in the as-cast condition approach those of higher-strength heat treated alloys. Castability is distinctly inferior, and full properties may not be realized for days, weeks, or longer periods of room-temperature hardening. Stability can be an issue addressed by artificial aging or heat treatment without quenching.

Alloys of this type include selected Al-Mg, Al-Zn-Mg, and Al-Zn-Mg-Cu alloys such as 535.0, 712.0, 771.0, and 772.0.

Typical applications include:

- Tooling plate
- Complex thin-walled shapes such as impellers and cooling fans
- Explosion-proof enclosures
- Electrical fittings
- Brazed parts
- Machinery
- Instrument cases
- Marine components
- Pistol frames
- Food and beverage processing
- Decorative parts
- Reflectors
- Optical systems

2.6.5 Bearings

Aluminum-tin alloys 850.0, 851.0, 852.0, and 853.0 are specialized compositions displaying excellent bearing characteristics under moderate loads and with effective lubrication. Castability, hardness, compressive yield strength, and other properties are influenced by alloy variations involving silicon and copper additions.

The principal applications for these alloys are bushings and bearings.

2.6.6 High-Strength Alloys

High-strength alloys include compositions designed to provide high strength and ductility and in the case of premium engineered castings also imply high levels of internal soundness and microstructural refinement. Alloys considered premium strength by definition and specification (AMS-A-21180) are A201.0, A206.0, 224.0, 249.0, 354.0, A through D356.0, A through D357.0, 358.0, and 359.0. Other alloys displaying high strength are 204.0, 206.0, C355.0, and metal-matrix composite compositions.

Applications include:

- Missile bodies
- Missile fins
- Aircraft pylons
- Aircraft canopies
- Wing flaps
- Speed brakes
- Hatch covers
- Hydraulic pumps
- Automotive suspension systems and cross-members
- Fuel pumps
- Brake valves
- Armored cupolas
- Aerospace structural parts

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Aluminum Alloy Castings: Properties, Processes, and Applications
J.G. Kaufman, E.L. Rooy, p 21-37
DOI:10.1361/aacp2004p021

CHAPTER 3

Aluminum Casting Processes

3.1 History

Aluminum alloy castings were first produced using processes that had been in historical use for other metals. It is generally believed that the art of metal casting was first practiced more than 5500 years ago, when shaped cavities were carved or impressed into molds of soft minerals and clay. Naturally occurring copper, silver, and gold were melted and solidified in these cavities. Brass, bronze, tin and zinc artifacts, weapons, and tools were cast as extractive metallurgy developed, and more complex molds of sand and clay mixtures evolved. These methods were duplicated later for other metals including iron and steel.

The relatively attractive engineering properties of aluminum—low melting point and castability—quickly led to the adoption of existing casting processes and to developments that broadened the means by which engineered shapes could be produced from molten metal.

Iron or steel dies had been used in casting print type in lead-base alloys in the 17th century. Iron molds were also used in colonial times to cast pewter. Intensive efforts to employ iron and steel molds in the casting of aluminum resulted in commercial "permanent mold" operations by the first decade of the 20th century.

Pressure die casting came into existence in the early 1820s in response to the expanding need for large volumes of cast print type. The injection of metal under pressure into metallic dies was at first purely mechanical, using hand cranks. Later, pneumatic and hydraulic systems were used as applications grew to include bicycle, phonograph, and consumer durable parts. By 1870, jobbing die casters were producing lead and other low-temperature metals with a surprising degree of automation. Progress in die casting aluminum was limited until the development of the cold chamber process in the 1920s.

Aluminum can be cast by essentially all existing processes including pressure die casting, permanent mold, clay/water bonded sand, chemically bonded sand, plaster mold, and investment casting. Important variations include molding and pattern distinctions such as lost-foam (evaporative pattern), shell and V-mold, and process derivatives such as squeeze casting, low-pressure permanent mold, vacuum riserless casting, and semisolid forming based on rheocasting/thixocasting principles.

3.2 Casting Process Selection

Many factors influence the selection of a casting process for producing a specific part. Process selection is strongly influenced by part requirements that are often the basis for defining alloy candidates that in turn influence the range of process choices. The most important process selection criteria are:

- Casting process considerations: requirements for fluidity, resistance to hot tearing, minimization of shrinkage tendencies
- Casting design considerations: draft, wall thickness, internal passages
- Mechanical property requirements: strength and ductility, hardness, fatigue strength, toughness, impact strength, specification limits
- Physical property requirements: electrical and thermal conductivity, specific gravity, expansion characteristics
- Process requirements: machinability, brazeability, weldability, impregnation, and chemical finishing
- Service requirements: pressure tightness, corrosion resistance, wear resistance, elevated-temperature strength, dimensional and thermal stability
- Economics: volume, productivity, process yield, material costs, tooling costs, cost of machining, welding, and heat treatment

Many aluminum alloy castings can be produced by any of the available methods. In most cases, dimensions, design features, and material property requirements limit the range of candidate processes. Compromises in specified criteria are made to facilitate the use of the most cost-effective process.

3.2.1 Casting Design

Design considerations include size, shape, complexity, wall thicknesses, and required dimensional accuracy. Parts with undercuts and complex internal passageways can usually be made by sand, plaster, or investment casting, but may be impractical or impossible to produce in permanent mold or pressure die casting.

3.2.2 Specification Requirements

Conformance to specification requirements including mechanical and physical properties may limit process choice. Metallurgical

characteristics also vary as a function of cooling rates and solidification conditions imposed by differing casting processes. An alloy selection imposed by specified requirements and metallurgical considerations often dictates the casting process.

3.2.3 Volume of Production

The number of castings that are estimated to be required is a major factor in the choice of casting method. Loose or simple patterns may be used for sand cast prototypes or when only one or a few parts are required. When production is limited, tooling cost dominates. For larger production volumes, tooling costs, though significant, become less important. As volume requirements increase, the trend is toward automated molding processes, permanent molds, and die casting. For extended production in die and permanent mold operations, more expensive, difficult-to-machine tool steels provide improved life. Recent developments for reducing tooling costs include near-net-shape forming of dies, composite die materials, the deposition of hard, wear-resistant die surfaces, and in situ bonding of dissimilar materials by laser and high-intensity infrared technologies.

3.2.4 Costs

Costs are strongly influenced by process choice. Tooling costs associated with die and permanent mold casting are justified by higher levels of production and product reproducibility. The use of high-speed molding machines in volume sand casting improves production rates with increased capital and maintenance costs. Low-volume investment castings require precise patterns, hand mold assembly, and pouring practices that are justified by the extreme detail, accuracy, and finish of the final product. Premium engineered castings are typically low volume and high cost. When two or more casting processes are capable of satisfying part requirements, selection is dictated by unit cost.

3.2.5 Quality

Quality factors are also important in the selection of the casting process. Quality refers to the degree of internal soundness and to the mechanical properties and performance characteristics that are a reflection of alloy chemistry, molten-metal quality, solidification conditions, microstructural features, and soundness. The casting process dictates solidification conditions and, to a large extent, variations in microstructural features and soundness. The selected casting process must be competent to deliver the required level of quality.

3.3 Casting Process Technology

3.3.1 Expendable and Nonexpendable Mold Processes

Casting processes for aluminum may be categorized as involving expendable or nonexpendable molds. In sand casting, for example, the mold is destroyed when the casting is produced. Similarly, plaster and investment castings are made in molds that cannot be reused. Permanent molds and dies are reused, although each has finite life based on the number of castings that can be produced before wear, heat checking caused by thermal fatigue, or other conditions that affect their acceptability for continued production.

Sections 3.4 and 3.5 describe casting technologies under expendable and nonexpendable mold processes.

3.3.2 Pressure versus Gravity

A second important factor in categorization of aluminum casting processes is whether molten metal flows by gravity into the die or mold cavity or is forced under pressure. Casting by injection under pressure requires nonexpendable dies and is commonly referred to as pressure die casting. Countergravity processes that employ low-pressure differentials such as low pressure, displacement, or pumped systems for mold filling are considered variations of either expendable or gravity permanent mold processes.

3.3.3 Gating and Risering

There is a commonality in practices and terminologies for gravity casting in both expendable and nonexpendable molds. Molten metal is normally introduced to the mold cavity in an arrangement referred to as the gating system (Fig. 3.1, 3.2). It consists of a pouring basin leading to a downsprue through which molten metal is delivered to the parting plane of the mold. From the base of the downsprue, metal is conveyed along the casting periphery in runners that supply metal to in-gates from which metal enters the casting cavity. Risers—volumes of heat and pressure-differentiated

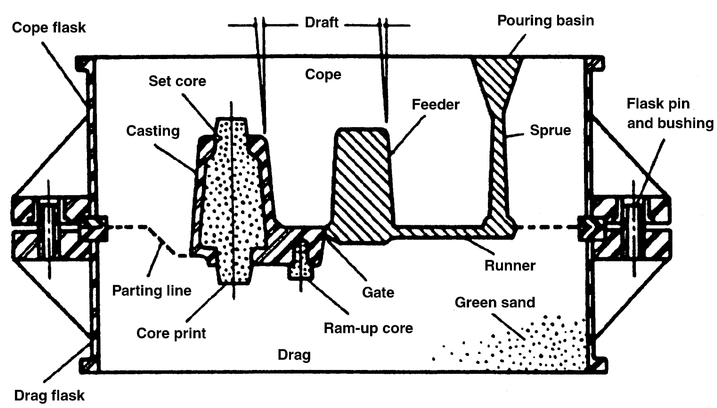

Fig. 3.1 Typical sand mold gating. Source: Ref 1

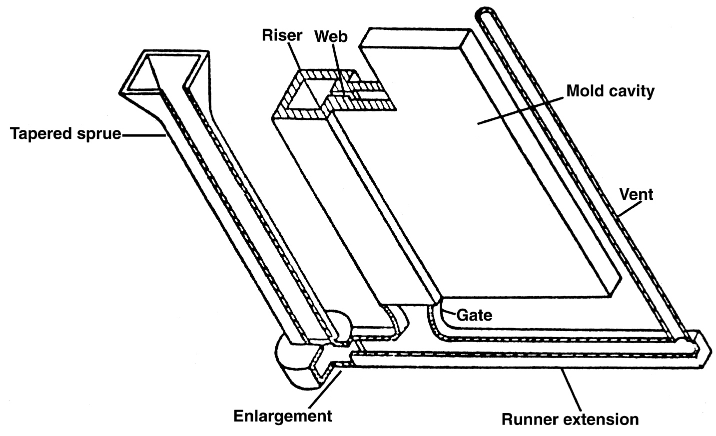

Fig. 3.2 Typical permanent mold gating. Source: Ref 2

molten metal—are strategically located external to the mold cavity to compensate for volumetric shrinkage as solidification of the casting progresses. The gating system is comprehensively designed to minimize turbulence and prevent aspiration.

Pressure die castings are filled through runners and in-gates, but risers are not normally used because solidification rate limits their effectiveness (Fig. 3.3). Instead, internal soundness is promoted by die design features, elaborate mold cooling, and pressure intensification during the shot cycle.

Most sand castings are produced in molds with a horizontal parting plane, while the parting plane in most permanent mold casting is vertically oriented. Pressure die castings are produced with both horizontal and vertical parting-plane orientation. In horizontally parted molds, the upper mold half is referred to as the cope, and the lower, the drag.

3.4 Expendable Mold Gravity-Feed Casting Process and Its Variations

3.4.1 Sand Casting

Green and Dry Sand. Sand casting involves the forming of a geometrically dimensioned impression in sand. The process includes green sand and dry sand casting. Green sand refers to the use of uncured bonding systems, usually a blended mixture of sand, clay, and water. In the dry sand process, resins, oil, or other chemical binding agents are used to precoat the molding sand. The dry sand mold is then thermally or chemically cured. Another dry sand method reacts carbon dioxide (CO_2) gas with sodium silicate in the sand blend to form a silica gel bond.

The important parameters of molding sand are compressive strength and permeability. Tests for each are routinely performed

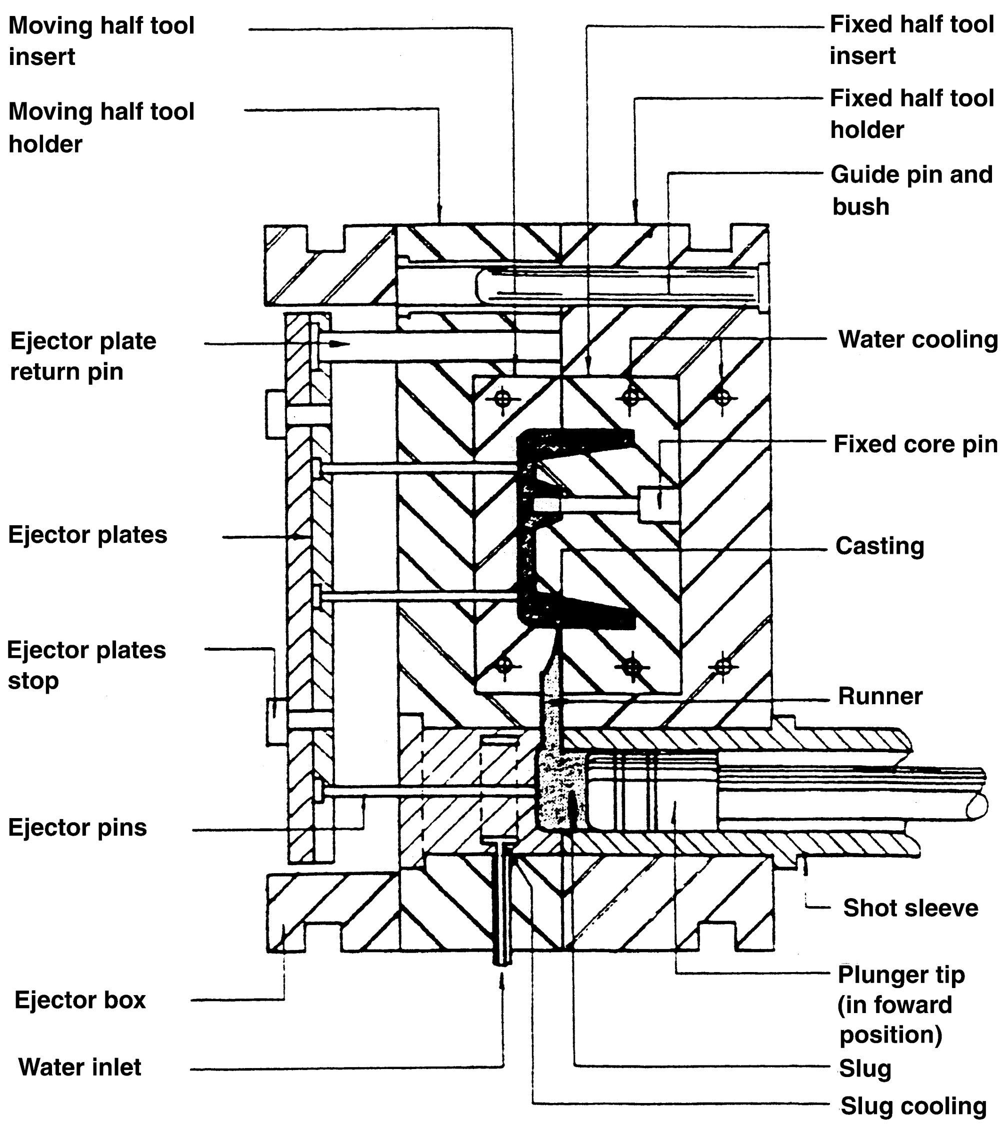

Fig. 3.3 Typical die casting gating. Source: Ref 3

for quality assurance. The mold must have sufficient strength to maintain its shape through the casting process and sufficient permeability to permit the air, and gases formed during pouring, to evacuate the mold cavity as the metal enters. Compressive strength and permeability in green sand are functions of sand particle size and shape, moisture and binder contents, and the degree of compaction applied in forming the mold.

The advantages of typical sand casting are versatility in a wide variety of alloys, shapes, and sizes. Alloys considered hot short because of cracking tendencies during solidification are more easily cast in green sand since molds offer reduced resistance to dimensional contraction during solidification. Lower mold strength is also advantageous for parts with widely varying section thicknesses and intricate designs. These advantages are diminished in chemically bonded molds, which display greater rigidity than green sand molds.

There are only practical limitations in the size of the parts that can be cast. Minimum wall thickness is normally 0.15 in. (4 mm), but thicknesses as little as 0.090 in. (2 mm) can be achieved.

Among disadvantages are relatively low dimensional accuracy and poor surface finish; basic linear tolerances of ±0.03 in./in. (±30 mm/m) with a minimum tolerance of 0.020 in./in. (20 mm/m), and surface finishes of 250 to 500 μin. (6 to 13 μm) root mean square (rms). Chemically bonded sands offer improved surface finish and dimensional accuracy, and relatively unlimited shelf life, depending on the type of binder used. Achievable dimensional tolerances can be substantially improved using precision methods in the forming and assembly of dry sand mold components. Surface quality can be improved by using a finer grade of facing sand in the molding process.

Strength is typically lower as a result of slow solidification rates. Mechanical properties are improved by using sands such as zircon and olivine with higher heat capacity than silica and by the use of copper, iron, or steel chills at strategic locations in the mold.

Sand casting involves minimum tooling and equipment cost when smaller numbers of castings are to be produced.

Sand Molding. In both green and dry sand processes, the mold is formed by compacting the preconditioned sand over the pattern. In floor or hand molding, the sand is compacted using manual or pneumatic rams; for pattern plates (match plates), machines use jolt/squeeze mechanisms to ensure mold integrity. Automatic molding machines provide a high degree of uniformity and very high mold production rates.

Patterns may consist of wood, composite, or metal plates containing the casting impression or may consist of loose pieces assembled in the form to be cast. After compaction of the molding sand, the pattern is carefully removed, leaving a cavity in the shape of the casting to be made. A dusting of calcium carbonate or other parting compound on the pattern surface is helpful in facilitating the separation of the pattern from the mold. A small amount of vibration through transducers attached to the match plate also facilitates pattern removal.

The runners and in-gates are usually integral to the pattern, but may also be manually cut into the sand by the molder. A pattern of the sprue is separately placed on the pattern before sand is introduced.

If the casting contains internal passages or undercuts, dry sand cores may be used. In these cases, the mold includes locating points and additional impressions or prints for precisely positioning the cores after pattern removal and before final mold assembly. In rare cases, aluminum chaplets may be used to support the core position.

Molten metal is poured into the mold, and after it has solidified, the mold is physically removed from the casting. Removal is by physical means including vibration.

Casting quality is determined to a large extent by foundry technique. Proper molten metal processing, metal-handling and gating design and practices including the selective use of chills are necessary for obtaining sound castings. Complex castings with varying section thicknesses will be sound only if proper techniques are used.

While the principles of sand casting are relatively simple, a large number of process variations are in use that typically involve expendable pattern materials and molding methods.

3.4.2 Evaporative (Lost-Foam) Pattern Casting (EPC)

Lost foam is a sand casting process that uses an unbonded sand mold with an expendable polystyrene pattern. This process is somewhat similar to investment casting in that an expendable pattern is used to create the mold cavity. Unlike investment casting, the pattern vaporizes during the pouring of molten metal rather than before pouring.

The EPC process employs a foamed polystyrene pattern packed in unbonded sand. The polystyrene model is coated with a thin layer of ceramic or refractory wash that seals the pattern surface. The pattern is sequentially decomposed by the heat of the molten metal, thus replacing the foam pattern and duplicating the features of the pattern in the solidified casting. Use of the process has increased rapidly, especially in large-volume automotive foundries, and many casting facilities are now dedicated to the production of castings by this method (Fig. 3.4).

The major difference between sand castings and castings made by the EPC process is the extent of subsequent machining and cleaning operations required. Evaporative pattern castings are con-

Fig. 3.4 Typical castings produced by the evaporative pattern casting (EPC) process

sistently poured at closer tolerances with less stock for grinding, machining, and finishing. Dimensional variability associated with core setting and the mating of cope and drag are eliminated. The use of untreated, unbonded sand simplifies sand processing, handling, and reclamation. Casting cleaning is also greatly reduced and can often be eliminated because of the absence of flash, sand adherence, and resin stains. Further benefits of the EPC process result from the freedom in part design offered by the process. Assembled patterns can be used to make castings that cannot be produced by any other high-production process.

3.4.3 Shell Mold Casting

In shell mold casting, molten metal is poured into a shell of resin-bonded sand only 0.4 to 0.8 in. (10 to 20 mm) thick. The mold is formed by introducing the chemically coated sand to a heated pattern that thermally cures the bond. By controlling the core mold temperature and cycle, the depth of cure can be controlled to the desired thickness. Cured mold sections are removed and assembled for pouring, usually backed by unbonded or green sand (Fig. 3.5). Shell mold castings surpass ordinary sand castings in surface finish and dimensional accuracy and cool at slightly higher rates; however, equipment and production costs are higher, and the size and complexity of castings that can be produced are limited.

Fig. 3.5 Shell molds assembled before pouring. Source: Ref 1

3.4.4 Plaster Casting

In this method, either a permeable (aerated) or impermeable plaster is used for the mold. The plaster in slurry form is poured around a pattern. When the plaster has set, the pattern is removed and the plaster mold is baked to remove free water and reduce waters of hydration. The high insulating value of the plaster allows castings with thin walls to be poured. Minimum wall thickness of aluminum plaster casting is typically 0.060 in. (1.5 mm). Plaster molds have high reproducibility, permitting castings to be made with fine details and close tolerances; basic linear tolerances of $\pm$0.005 in./in. ($\pm$5 mm/m) are typical. The surface finish of plaster castings is excellent; aluminum castings attain finishes of 50 to 125 μin. (1.3 to 3.2 μm) rms.

For complex shapes, such as some precision impellers and electronic parts, mold patterns made of rubber are used because their flexibility makes them easier to withdraw from the molds than rigid patterns. Intricate plaster castings may also be produced using polystyrene or other expendable pattern materials such as those used in investment casting.

Mechanical properties and casting quality depend on alloy composition and foundry technique. Slow cooling due to the highly insulating nature of plaster molds magnifies solidification-related problems such as hydrogen pore formation and shrinkage voids and reduces strength and ductility.

For many plaster cast parts, there are only limited capabilities for improving internal soundness and properties through traditional gating and risering approaches. The configuration of impellers and other rotating parts subject to strict dimensional requirements as well as strengths compatible with high rotational stresses permits the use of extensive chilling of the shaft and base for purposes of improving internal soundness and mechanical property performance. These techniques are further enhanced when combined with nonturbulent mold filling by low-pressure or other countergravity methods. Figure 3.6 shows plaster cast alloy 224.0 impellers that were produced through a low-pressure method.

3.4.5 Investment Casting

Investment casting of aluminum most commonly employs ceramic molds and expendable patterns of wax, plastic, or other low-temperature melting materials. In the ceramic shell method, assembled patterns are invested in a ceramic slurry by repetitive immersion and air drying until the desired shell thickness has been formed. In the solid mold investment method, the assembled pattern is immersed in a container of sufficient size for ceramic slurry to encase and set around the pattern. In either case, the mold is placed in an autoclave to remove the pattern and then fired at high temperature to remove all free water and organic materials and to cure the binding system being used. Molds are typically preheated and poured under partial vacuum. Christmas-tree gating systems are employed to produce small multiple parts in one mold.

Aluminum investment castings can have walls as thin as 0.015 to 0.030 in. (0.40 to 0.75 mm), basic linear tolerances of ±5 mils/in. (±5 mm/m) and surface finishes of 60 to 90 μin. (1.5 to 2.3 μm).

Because of porosity and slow solidification, the mechanical properties of many aluminum investment castings are typically lower than those demonstrated by other casting processes. The interest of the aerospace and other industries in the combination of accurate dimensional control with controlled mechanical properties has resulted in the use of improved technologies to produce premium-quality castings by investment methods. Castings in the premium-strength range can be achieved with molten metal treatments, gating, and solidification conditions that are not typical for conventional investment castings.

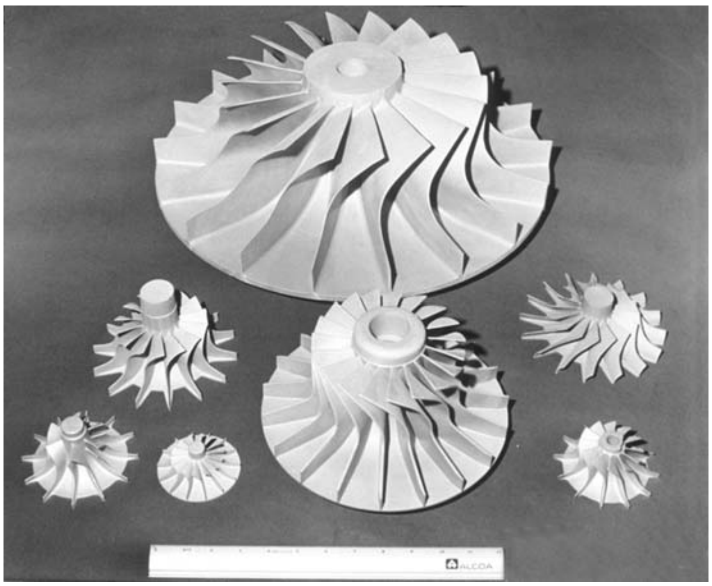

Fig. 3.6 Alloy 224.0 impellers produced by low-pressure plaster casting

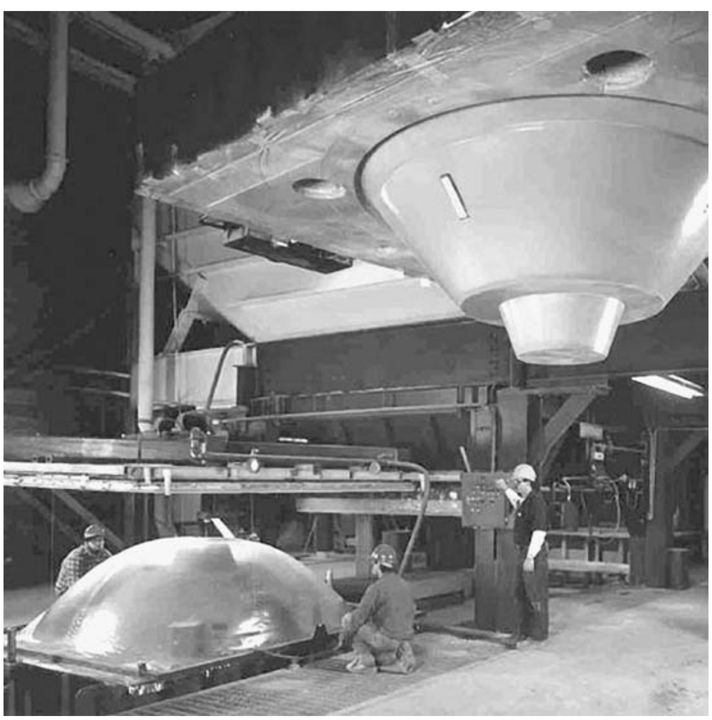

Fig. 3.7 Vacuum molding unit. Source: Ref 1

Investment casting applications include: instrument parts, impellers, compressor vanes, gears, ratchets, pawls, scrolls, speed brakes, wing tips, and aircraft pylons.

3.4.6 Vacuum Mold (V-Mold) Casting

A heated plastic film is drawn over the pattern by vacuum. Unbonded sand is filled against the plastic-covered pattern within a vented flask and compacted by vibration. A vacuum is drawn through the flask after an unheated plastic film is placed over the back of the mold, creating a mold vacuum package. Pouring takes place with the vacuum retained or reapplied (Fig. 3.7).

Advantages are surface finish, minimum wall thickness, and reduced draft requirements. Disadvantages are tooling costs and size limitations imposed by maximum flask dimensions.

3.5 Nonexpendable (Permanent) Mold Gravity Feed Casting Process and Its Variations

3.5.1 Permanent Mold Casting

In principle, permanent mold casting is analogous to expendable mold casting processes. In this case the molds are machined cast, wrought or nodular iron, cast steel, or wrought steel and can be reused repetitively until damage, wear, or the effects of thermal fatigue necessitate repair or replacement (Fig. 3.8). The ability to form internal passages involves metallic or sand cores. Intricate details and undercuts can often be cast using segmented steel cores. Sand cores become necessary when the design prohibits drawing the core after the casting has solidified. When sand cores are used, the process is referred to as "semipermanent mold" casting.

Permanent mold tooling is typically more expensive than that required for sand casting and other expendable mold processes and is justified by the volume of production. The volume of production also dictates the extent of process automation. Molds can be manually operated or extensively automated. Production rates of automated multimold operations are high, and parts display consistent dimensional characteristics and properties.

While the principles and mechanics of gravity casting are similar, the metallurgical structure of permanent mold castings reflects the refinement of higher solidification rates. Typical and specified minimum mechanical properties including ductility are higher than those of expendable mold castings. The improved mechanical properties of permanent mold castings provide part of the justification for selecting this process over competing gravity casting options.

The same terminologies used in expendable mold gating apply. There is a downsprue into which molten metal is introduced from a pouring basin, from which the metal flows into runners, risers, in-feeds, and casting cavity. Directional solidification is promoted by selective chilling of mold sectors by air, mist, or water. An insulating coating is used to protect the mold from the molten aluminum and to facilitate removal of the casting from the mold after solidification is complete. Typical mold dressings or washes are suspensions of talc, various metal oxides such as zirconia,

chromia, iron oxide and titania, colloidal graphite and calcium carbonate in water, and sodium silicate. The thickness and thermal characteristics of these coatings are used to locally increase or decrease heat absorption during solidification. As a result of wear, these coatings must be periodically repaired or replaced to ensure consistent process performance and casting results. Mold surfaces are periodically blasted with dry ice or mild abrasives to remove coatings and scale after which new mold coatings are applied.

The permanent mold process is less alloy tolerant than most expendable mold processes. The most popular permanent mold alloys display superior castability such as those of the Al-Si, Al-Si-Mg, and Al-Si-Cu (Mg) families. Mold rigidity is a challenge in the casting of hot-short alloys in which liquidus-solidus range and elevated-temperature strength combine to increase the tendency for cracking during and after solidification. Determined efforts to cast even the most difficult foundry alloys such as low-iron aluminum-copper alloys have nevertheless been successful, and alloys with limited castability are routinely cast in permanent molds.

Permanent mold castings can be produced in sizes ranging from less than a pound to more than several hundred pounds. Surface finish typically varies 150 to 400 μin. (3.8 to 10 μm). Basic linear tolerances of about ±0.01 in./in. (±10 mm/m), and minimum wall thicknesses are about 0.100 in. (2.5 mm).

Fig. 3.8 Permanent mold machined from steel. Source: Ref 1

3.5.2 Low-Pressure Die Casting (LP), Pressure Riserless Casting (PRC)

In this process, permanent molds are mounted over a sealed furnace. A tube extends from the mold cavity into the molten metal below. By pressurizing the furnace, metal is forced through the tube into the mold cavity (Fig. 3.9). When the metal has solidified, the pressure is relieved, the mold is opened, and the casting is removed in preparation for repeating the cycle.

Most low-pressure casting has been confined to radially symmetrical designs, but a wide range of nonsymmetrical parts have also been produced. Nearly all automotive wheels are cast by this process (Fig. 3.10, 3.11).

Process parameters include (a) the rate at which pressure is applied, which regulates mold filling, (b) pressure, which is relatively unimportant once solidification begins, and (c) thermal gradients, which are essential for establishing directional solidification. As in conventional permanent mold, these gradients are established by the selection and controlled thicknesses of mold coatings and by selective chilling of mold sections. Since most low-pressure castings are produced using only one metal entry point and since risers normally necessary to avoid internal shrinkage voids are not typically used, the gross-to-net weight ratio is low and trimming and finishing operations associated with gating are minimized.

The low-pressure casting cycle is dictated by the solidification of metal at the junction of the fill-tube and mold cavity.

While countergravity metal flow into the mold cavity is quiescent, the process does present the risk of inclusion contamination. When the mold is opened and the casting is removed, the vacuum seal that existed at the liquid-solid interface is broken and molten metal remaining in the tube falls to the furnace metal level. The cycling of metal flow vertically in the fill tube can result in the buildup of oxides on the inner surfaces of the fill tube whether the

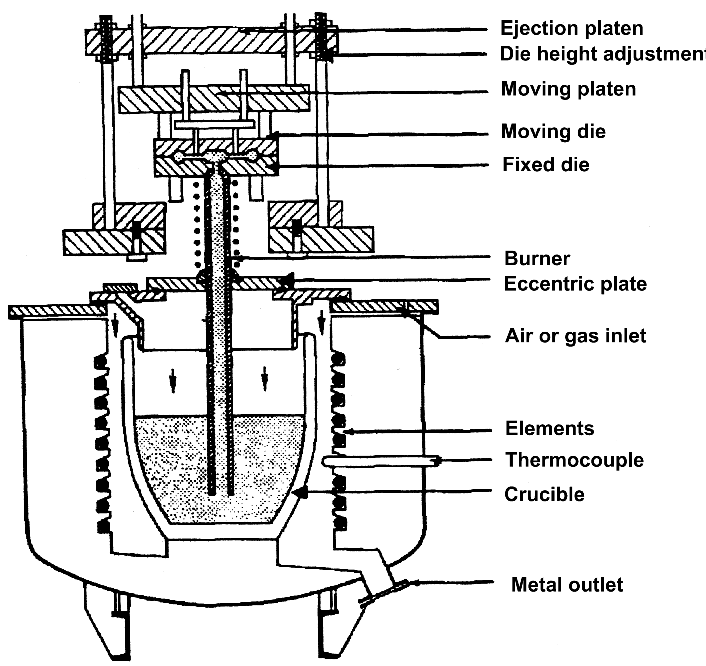

Fig. 3.9 Low-pressure permanent mold. Source: Ref 1

tube is ceramic or coated metal. To minimize this condition, back pressure can be maintained in the system so that molten metal is retained at an elevated level in the fill tube at all times. It is also possible to replenish metal in the furnace with each cycle by valving rather than periodically refilling when the metal in the furnace is nearly depleted. Filtration of metal at the point of entry into the mold is routinely used to prevent included matter from contaminating the casting. Filtration may consist of steel screens, ceramic strainers, or fused or foamed porous ceramics.

Fig. 3.10 Alloy A356.0 alloy automotive wheels produced by low-pressure casting

3.5.3 Vacuum Riserless Casting (VRC)

The use of vacuum rather than pressure to introduce molten metal into steel dies has significant advantages over low-pressure casting. The molten metal bath is open and accessible. Molten metal level can be maintained within a narrow range in close proximity to the mold entry point so that the vertical dimension between the metal surface and the mold cavity can be minimized.

Limitations are in the size and cost of molds that can be engineered to apply and retain vacuum pressures.

A high degree of mold chilling has been used to enhance metallurgical structures, improve mechanical properties, and shorten cycle times. The VRC process is ideally suited for automation and high production rates to produce castings with exceptional surface quality and metallurgical properties. Examples of VRC products are shown in Fig. 3.12.

3.5.4 Centrifugal Casting

Centrifugal force in aluminum casting involves rotating a mold or a number of molds filled with molten metal about an axis. Cylindrical or tubular shapes may be centrifugally formed in vertically or horizontally rotated drums, while conventional castings are produced by the rotation of one or more molds about a vertical axis. Metal may be introduced before or during rotation.

Baked sand, plaster, or graphite molds have been used, but iron and steel dies are most common. Centrifugal castings are generally, but not always, denser than conventionally poured castings and offer the advantage of greater detail.

Wheels, wheel hubs, motor rotors, and papermaking and printing rolls are examples of aluminum parts produced by centrifugal casting. Aluminum alloys suitable for permanent mold, sand, or plaster casting can be cast centrifugally.

Fig. 3.11 Variety of parts, including automotive pistons, metallurgically bonded diesel engine pistons, compressor pistons, cylindrical and journal bearings, anodes, and cookware, produced by the low-pressure casting process

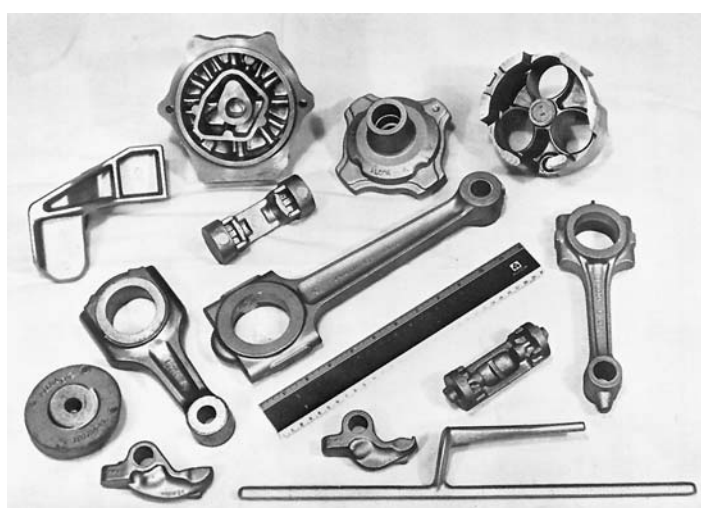

Fig. 3.12 Examples of castings produced by the vacuum riserless casting (VRC) process include rocker arms, compressor pistons, connecting rods, trowel handles, valve components, and other parts

3.5.5 Squeeze Casting

Although a number of process developments have been referred to as squeeze casting, the process by which molten metal solidifies under pressure within closed dies positioned between the plates of a hydraulic press is the only version of current commercial interest. The applied pressure and retained contact of the metal with the die surface improves heat transfer and inhibits hydrogen precipitation and shrinkage void formation. The result is a denser, fine-grained casting with excellent mechanical properties.

Squeeze casting has been successfully used for a variety of ferrous and nonferrous alloys in traditionally cast and wrought compositions. Applications of squeeze-cast aluminum alloys include reciprocating engine pistons, brake rotors, automotive and truck wheels, and structural automotive frame components (Fig. 3.13). Squeeze casting is simple and economical, is efficient in its use of raw material, and has excellent potential for automated operation at high rates of production.

3.5.6 Semisolid Forming

Semisolid forming incorporates elements of casting, forging, and extrusion. It involves the near-net-shape forming of metal parts from a semisolid raw material that incorporates a uniquely nondendritic microstructure.

Mechanical or electromagnetic force is employed during billet solidification to fragment the solidifying structure. The result is a spherulitic structure that behaves thixotropically in the liquidus-solidus range. The billet retains its shape at closely controlled temperatures above the melting point at which the shear strength is low, even at relatively high percent fraction solid. When the billet has been reheated, it is forced into dies under pressure to form a casting that retains the characteristics of the starting billet microstructure. Just as important, the mold cavity is filled without the turbulence associated with gravity pouring or the injection of molten metal, and internal porosity formation is minimized by reducing the volume of liquid metal that solidifies from the semisolid condition (Fig. 3.14).

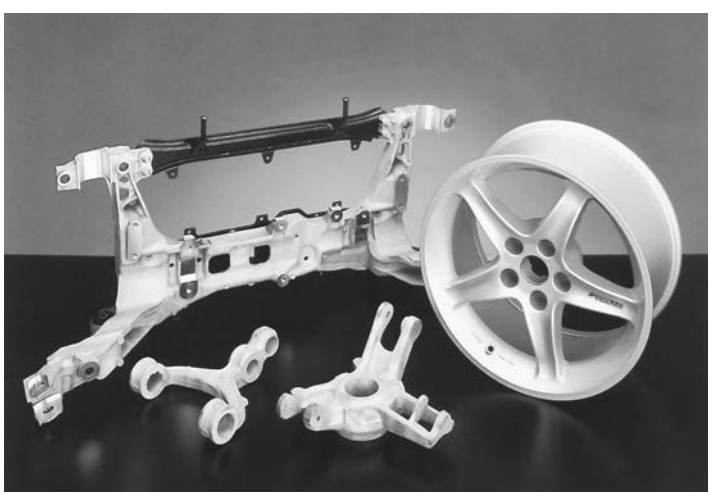

Fig. 3.13 Automotive parts produced by the squeeze casting process. Courtesy of UBE Industries

A number of alternative approaches to the production of the semisolid raw material have been or are being developed. A process in which particle ingots are continuously fed and mechanically stirred to provide the required semisolid state and microstructure has been developed and used in magnesium alloy casting production. The incompatibility of materials of containment with sufficient strength for this process in molten aluminum remains to be overcome. Attempts to eliminate expensive thin-cast billet through slurry approaches in mold filling have also been undertaken.

Semisolid forming is more costly than conventional casting, but offers unique properties and consistently excellent quality. In addition, the viscous nature of semisolid alloys provides a natural environment for the incorporation of third-phase particles in the preparation of reinforced metal-matrix composites.

Specialized billets are commercially available, and semisolid-formed applications are broadening in the aerospace, automotive, military, and industrial sectors. The process represents an alternative to conventional forgings, permanent mold, investment and die castings, impact extrusions, machined extrusion profiles, and screw machine products. Applications include automotive wheels, master brake cylinders, antilock brake valves, disk brake calipers, power steering pump housings, power steering pinion valve housings, compressor housings, steering column parts, airbag containment housings, power brake proportioning valves, electrical connectors, and various covers and housings that require pressure tightness.

3.6 Pressure Die Casting and Its Variations

The production of aluminum alloy castings by the die casting process exceeds that of all other processes. It is ideally suited for high production rate and volume production of dimensionally accurate parts with excellent surface finish. One of the important

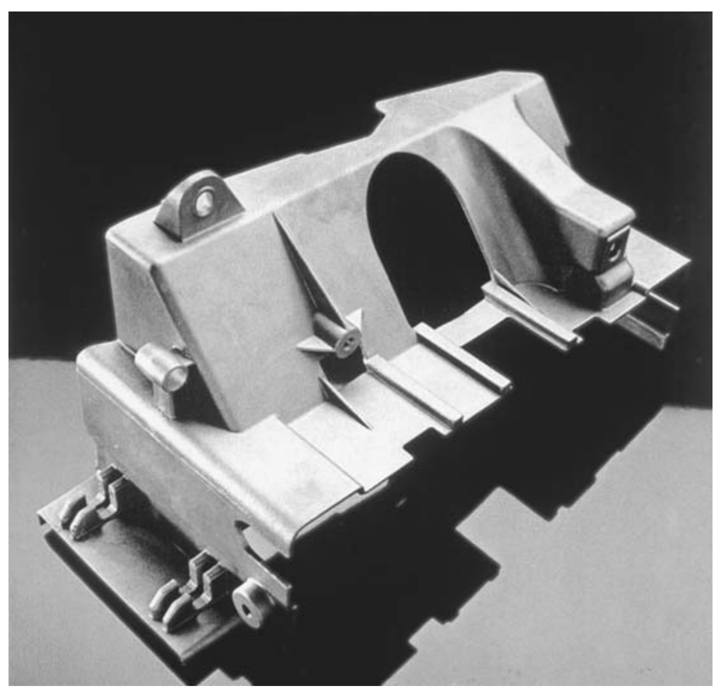

Fig. 3.14 Semisolid formed alloy A357.0 landing gear component

reasons for the success of die castings has been the development of high-speed precision equipment. Another is the extension of die casting technologies to larger castings with heavier wall thicknesses.

In pressure die casting, molten metal is injected under pressure into water-cooled dies. Pressure is maintained until the part has solidified. Molten metal usually enters the mold by the action of a hydraulic ram in a containment chamber (shot chamber), resulting in rapid filling of the mold cavity. While lubrication is required to facilitate the separation of the casting from the die surface, the dies are otherwise uninsulated. Dies are usually machined from high-quality tool steels.

The die casting process has undergone significant changes through the evolution of machine design and instrumentation as well as process development and controls. The demand for larger, more complex castings with improved quality and lower cost has led to the development and promotion of specialized die casting machines capable of higher rates of production and improved performance.

Die casting machines vary in type, size, and capacity.

There are two basic concepts, hot and cold chamber operation. In the hot chamber process, the shot chamber and piston are immersed in molten metal. Metals such as magnesium and zinc that do not aggressively attack the materials of construction can be efficiently cast by this method with production rate advantages. Despite intensive efforts to develop hot chamber process designs and materials that could be used in aluminum casting, none have been commercially successful. Except in rare cases, all aluminum die casting is performed in cold chamber equipment in which the shot chamber is filled with each cycle, and the chamber and piston assembly are not continuously in contact with molten aluminum.

Die casting machine designs are also differentiated by parting plane orientation. In practice, the dies are mounted on platens that can operate in either vertical or horizontal directions. Early die casting was typically performed with vertical die movement. Today, with exceptions, vertical die casting is restricted to rotor production.

Locking pressure defines the capacity of the machine to contain the pressure generated during the injection cycle. The larger the plan area of the casting and the greater the hydraulic pressure applied, the greater the required locking pressure. Die casting machines are designed with locking pressures from as little as 25 tonnes to more than 4500 tonnes corresponding to injection pressures of up to 40 ksi (280 MPa).

The principles of directional solidification and gravity-based gating and risering are essentially inapplicable to die casting. Gates and runners are used to convey metal from the shot chamber to the die cavity. Geometrical considerations are observed to minimize turbulence, air entrapment, and fragmentation of the metal stream, but no effort other than the use of sustained pressure is used to promote internal soundness. Techniques are used to intensify pressure during the solidification phase to decrease the volume fraction of internal porosity. With metal velocities exceeding 100 ft/s (30 m/s) and solidification rates exceeding 1800 ºF/s (1000 ºC/s), the greatest quality concern is entrapped gases including combustion or volatilization components of the lubricant and turbulence-related inclusions.

Rapid filling of the mold (20 to 100 μs) and rapid solidification under pressure combine to produce a consistently dense, fine-grained and highly refined surface structure with excellent properties including fatigue strength. Internal unsoundness affects bulk properties, the acceptability of machined surfaces, and pressure tightness. Impregnation is routine for die castings that must contain gases or liquids under substantial pressure. Internal unsoundness generally prevents full heat treatment and welding because of the risk of blister formation when die castings are exposed to elevated temperatures. Lower-temperature thermal treatments for stabilization or hardening are routinely used. In special cases and in restricted casting areas, limited welding can also be performed.

The die casting process is least alloy tolerant of important commercial casting processes. Solidification conditions require alloys of superior castability and that display good resistance to cracking at elevated temperatures. The highly castable alloys of the aluminum-silicon family are the most common. Of these, alloy 380.0 and its variations comprise about 85% of total die casting production. These compositions provide attractive combinations of cost, strength, hardness, and corrosion resistance in the as-cast state, with excellent fluidity and resistance to hot cracking. Aluminum-silicon alloys lower in copper, such as 360.0, 364.0, 413.0, and 443.0, offer improved corrosion resistance and excellent castability.

Hypereutectic aluminum-silicon alloys including 390.0 have become more important in wear-resistant applications.

Magnesium content is usually controlled at low levels to minimize oxidation and the generation of oxides in the casting process. Most commonly used die casting alloys specify restrictive magnesium limits. Nevertheless, aluminum-magnesium alloys can be die cast. Alloy 518.0, for example, is specified when the highest corrosion resistance and the brightest, most reflective finish are required.

Iron contents of 0.7% or greater are preferred to maximize elevated-temperature strength, to facilitate ejection, and to minimize soldering to the die face. Iron content is usually $1 \pm 0.3\%$, but greater concentrations are also used. Improved ductility through reduced iron content has been an incentive resulting in widespread efforts to develop a tolerance for iron as low as approximately 0.25%. These efforts focus on process refinements, design modifications, and improved die lubrication. At higher iron concentrations, there is a risk of exceeding solubility limits of coarse Al-Fe-Cr-Mn segregate at molten metal temperatures. Sludging or precipitation of segregate is prevented by chemistry controls related to metal temperature. A common rule is:

$$\text{Fe} + 2(\text{Mn}) + 3(\text{Cr}) \leq 1.7$$

where element values are expressed in weight percent.

Die casting is especially suited to production of large quantities of relatively small parts. Typical aluminum die castings weigh from a few ounces to more than 100 lb (50 kg).

Close tolerances and excellent surface finishes are characteristic. Aluminum alloys can be die cast to tolerances of ±4 mils/in. (±0.004 in./in.) and commonly have finishes as fine as 50 μin. (1.3 μm). Parts are cast with walls as thin as 0.040 in. (1.0 mm). Cores,

which are made of metal, are restricted to simple shapes that permit drawing or removal after solidification is complete.

3.6.1 Acurad Die Casting Process

An acronym for accurate, rapid, and dense, the Acurad process claimed a degree of directional solidification from thermal analysis, die cooling and gating design, modulated lower metal injection velocities, and intensified injection pressures during solidification through the use of a secondary plunger. In effect, Acurad represents a compromise between die casting and permanent mold principles.

3.6.2 High-Integrity Pressure Die Casting

The combination of optimal die casting practices marries metallurgical and mechanical capabilities to provide quality levels exceeding those of conventional die casting. Solid-state lubricants are used in place of volatile die lubricants. Dies, lubricants, and ejector systems are designed to facilitate casting removal at reduced iron levels. The die cavity is evacuated before injection. Molten metal processing to reduce dissolved hydrogen and entrained nonmetallics approximates that used for gravity casting. Molten metal handling and the transfer of molten metal to the shot chamber are nonturbulent, and the injection sequence is adjusted to promote nonturbulent die filling. Large, thin-wall automotive structures and other high-quality die castings are being produced that display strength, ductility, and toughness that cannot be achieved in other die casting processes. With improved internal quality, high-integrity die castings can be welded and heat treated, although some limitations still apply.

3.6.3 Pore-Free Pressure Die Casting

In the "pore-free" process, the die cavity is purged with oxygen before metal injection. The oxygen reacts with molten aluminum to form oxides that influence fluid flow and by being chemically consumed reduces the tendency for entrapment as gas pores. The oxides are concentrated in the casting surface after solidification so that inclusion effects on properties are minimized.

3.6.4 Vacuum Die Casting

The application of a partial vacuum to the die cavity evacuates air and volatilized lubricant from the mold before and during metal injection. Vacuum die casting reduces the tendency for air entrapment resulting from rapid and turbulent die filling. The improvement in soundness results in degrees of acceptability for welding and heat treatment.

3.6.5 Rotor Casting

Most cast aluminum motor rotors are produced in specialized compositions by smaller vertical die casting machines. The objective is consistent electrical performance. Alloys 100.0, 150.0, and 170.0 (99.0, 99.5, and 99.7% Al, respectively) specify impurity limits and ratios for the formation of intermetallics least harmful to castability and limit the concentrations of peritectic elements most detrimental to electrical conductivity. Titanium and vanadium are precipitated or complexed by boron additions. Iron and silicon contents are controlled with the objective of promoting αAl-Fe-Si formation that is less detrimental to castability. These impurity controls improve and minimize variations in conductivity and reduce the tendency for microshrinkage and cracking during solidification.

Because unalloyed aluminum can be purchased at lower cost than rotor alloys, there has been a trend for their substitution in rotor production. For example, P1020 unalloyed smelter ingot has the same purity as 170.2 but without impurity ratio controls and with uncontrolled titanium and vanadium content. Ignoring these differences results in variable electrical performance and poor castings.

Minimum and typical conductivities for each grade are:

Alloy	Conductivity, %IACS	
	Minimum	Typical
100.1	54	56
150.1	57	59
170.1	59	60

Rotor alloy 100.0 with larger concentrations of iron and other impurities displays superior die casting characteristics. With higher iron content, crack resistance is improved and there is a lower tendency for internal shrinkage. This alloy is recommended when the maximum dimension of the part is greater than 5 in. (125 mm).

For the same reasons, alloy 150.0 offers castability advantages over alloy 170.0.

For rotors requiring high resistivity for higher starting torque, conventional die casting or other highly alloyed compositions are used. The most common are 443.2 and A380.2. By choosing alloys such as these, conductivities from 25 to 35% IACS can be obtained. Experimental rotor alloys have been developed with conductivities as low as 18% IACS.

Although gross casting defects may adversely affect electrical performance, the conductivity of alloys employed in rotor manufacture is almost exclusively controlled by composition. Simple calculation using these values accurately predicts total resistivity and its reciprocal, conductivity, for any composition. An easy-to-use formula for conductivity that offers sufficient accuracy for most purposes is:

$$\text{Conductivity, \%IACS} = 63.50 - 6.9(\text{Fe} + \text{Si}) - 83(\text{Ti} + \text{V} + \text{Mn} + \text{Cr})$$

where element values are expressed in weight percent.

More accurate calculations may be made from the elemental resistivities given in Table 8.4, in Chapter 8.

3.7 Premium Engineered Castings

A premium engineered casting is one that provides higher levels of quality and reliability than found in conventionally produced castings. Premium engineering includes intimately detailed design and control of each step in the manufacturing sequence. The results are minimally variable premium strength, ductility, soundness, dimensional control, and finish. Castings of this classification are notable primarily for mechanical property performance that reflects extreme soundness, fine dendrite-arm spacing, and well-refined grain structure.

Premium engineered casting objectives require the use of chemical compositions competent to display superior properties. Alloys

considered to be premium-strength compositions are listed in specification AMS-A-21180, which is extensively used in the United States for premium casting procurement. They include A201.0, A206.0, 224.0, 249.0, 354.0, C355.0, A356.0, A357.0, D357.0, 358.0, and 359.0.

Premium engineered aluminum castings represent the culmination of decades of research and development involving molten metal treatment, methods for the removal of included matter, measurement or assessment of dissolved hydrogen, gating development, microstructural modification and refinement, casting processes, mold materials, and the development of high-strength, ductile alloys. Each of these developments was necessary to advance casting capabilities to meet an increasingly challenging range of application requirements. The marriage of superior technologies in all phases of casting design and production was essential for meeting the most difficult of these challenges. The incentive was the cost-effective replacement of more expensive wrought product assemblies by competent monolithic cast structures.

3.7.1 Melt Processing

The principles of sparging for the removal of dissolved hydrogen had been developed in the late 1920s and 1930s. The use of active gases such as chlorine and the physicochemical separation of entrained oxides and other nonmetallics by fluxing became known in the 1930s. The use of diffusers for more efficient gas fluxing was developed later.

By 1950, particulate filtration and countercurrent fluxing using nitrogen, argon, chlorine, and combinations of these gases became common for wrought alloy production, and variations of these processes were being used in gravity casting foundries.

The later development of rotary degasing systems was quickly adapted to foundry use.

3.7.2 Melt Quality Assessment

To a large extent, melt quality has been assessed by variations of the Straube-Pfeiffer test in which the relationship of hydrogen solubility and pressure was qualitatively measured. The absence of entrained oxides was assessed by their influence on hydrogen precipitation under reduced pressure. A semiquantitative approach using sample densities was developed and used extensively as a process control tool (Ref 4). For greater sensitivity, controlled vibration during sample solidification at absolute pressures of 0.04 to 0.10 psi (2 to 5 mm Hg) was employed. Real-time measurement of dissolved hydrogen by partial pressure diffusion in molten metal supplemented vacuum test results. Validation of hydrogen assessments was provided by solid-state extraction techniques.

3.7.3 Solidification

Academicians were largely responsible for improved mathematics-based understanding of solidification behavior. The parameters of metallurgical structure that were controlled in the solidification process were extensively studied. The relationships of dendrite arm spacing and grain size and type on physical and mechanical properties were established, and the influence of variations in soundness caused by hydrogen porosity, shrinkage, and inclusions on strength and ductility were broadly used in the development of new general procurement and nondestructive evaluation specifications and standards.

Trial and error in alloy development gradually gave way to more systematic construction based on experience and the predictable interrelationship of elements in soluble and insoluble phase formation under differing solidification conditions.

The principles of directional solidification are easily grasped, but their translation to practice for complex cast parts remains problematic. There are nevertheless excellent simulation models and programs for predicting static and dynamic solidification patterns for specific part designs.

3.7.4 Solidification Rate

The relationship of properties and dendrite arm spacing has significantly influenced the premium engineered casting effort. Solidification rate not only improves tensile properties, but also dramatically improves ductility. Exploiting this relationship with appropriate alloys moved engineered aluminum castings away from the image of brittleness and damage intolerance that historically characterized design engineers' perceptions.

3.7.5 Mold Materials

Investment casting produced small parts in which dimensional accuracy and surface finish were important criteria. Plaster molds were used in the production of dimensionally accurate cast parts such as impellers and tire molds. There were corollary pattern, mold material, and mold processing developments. Differences in the molding and heat extraction characteristics of differing sands were measured, and at the same time supplier developments in dry sand binders were studied and evaluated.

In permanent mold, variations in mold wash chemistry and application were used with air, mist, and water cooling to control solidification. On occasion, copper and ceramic inserts were designed into the mold to promote solidification directionality. The use of steel chills, contoured sections, and mold plates was normal in sand casting.

The use of all available mold components from most insulating (foamed plaster) to most rapid heat extraction (water-cooled copper) could be incorporated in mold designs to reproducibly alter solidification in order to promote the highest possible degree of internal soundness. Computer simulations of mold filling dynamics and solidification that incorporate differences in heat extraction through finite-element analysis are gradually supplanting art and instinct in process designs.

The result is a composite mold design of significant complexity using dry sand and at least several other mold materials for each configuration.

3.7.6 Alloys

All alloys employed in premium casting engineering work are characterized by optimal concentrations of hardening elements and restrictively controlled impurities. Although any alloy can be produced in cast form with properties and soundness conforming to a general description of premium values relative to corresponding commercial limits, only those alloys demonstrating yield strength, tensile strength, and especially elongation in a premium range belong in this grouping. They fall into two categories: high-strength

aluminum-silicon alloys containing magnesium or magnesium and copper, and alloys of the 2xx.0 series, which by restricting impurity element concentrations provide outstanding ductility, toughness, and tensile properties with notably poorer castability.

The minimum properties of premium-strength alloys might be considered 40 ksi (275 MPa) tensile strength, 30 ksi (205 MPa) yield strength, and 3.0% elongation. Much higher minima are routinely specified.

In all premium casting alloys, impurities are strictly limited for the purposes of improving ductility. In aluminum-silicon alloys, iron is controlled at or below 0.010% with measurable advantages in the range of 0.03 to 0.05%. Beryllium is present in A357.0 and 358.0 alloys, not to inhibit oxidation although that is a corollary benefit, but to alter the form of the insoluble phase to a more nodular form less detrimental to ductility.

Most of the compositions designated as premium engineered alloys had their origins in the 1950s and early 1960s. Alloy A356.0, registered in 1955, and B356.0 in 1956 were derivatives of 356.0 alloy which was originally developed in 1930. Similarly, alloy C355.0 dates from 1955, while the parent 355.0 was first used in 1930. Alloys 359.0 and 354.0 were developed in 1961. Alloy A357.0 (1962) had its origins in Tens-50 alloy that was also first registered in 1961. Examples of premium engineering castings in alloys A357.0 or D357.0 are shown in Fig. 3.15 to 3.19.

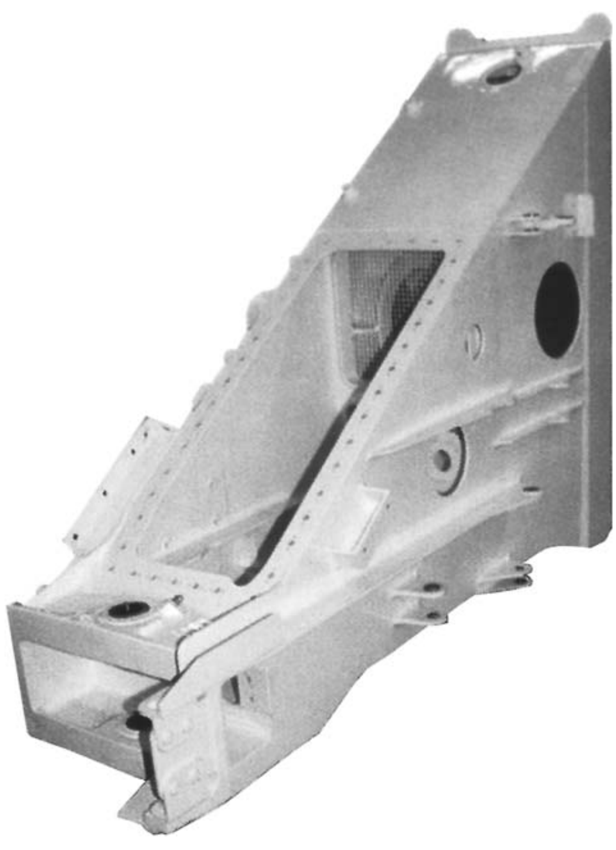

Fig. 3.15 One-piece alloy D357.0 main landing gear door uplock support for the 767 airplane. The casting replaced a sheet metal assembly; the conversion eliminated 27 separate parts and reduced assembly time by 65%. Source: Ref 5

The extremely high strength and toughness capabilities of various typically 4.5% Cu alloys including 201.0, 204.0, 206.0, 224.0, and 249.0 have their roots in 295.0 alloy, which dates from 1921 and in earlier European compositions. Most were introduced or appeared in refined versions during the period from 1968 to 1974.

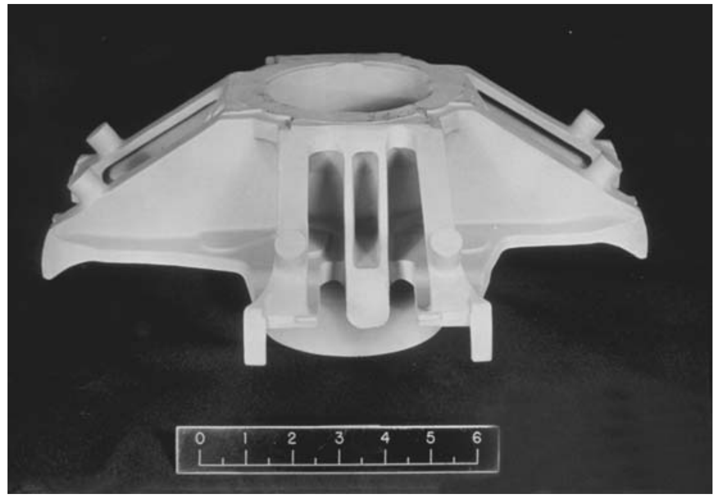

Fig. 3.16 Premium engineered casting helicopter rotor hub

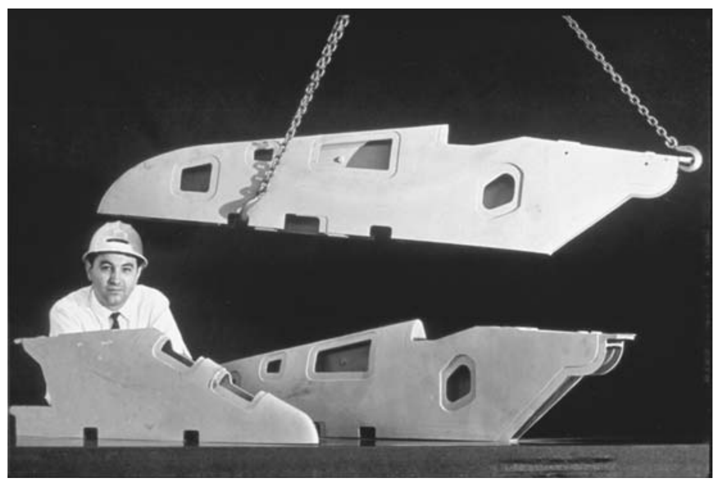

Fig. 3.17 Premium engineered casting aircraft pylons

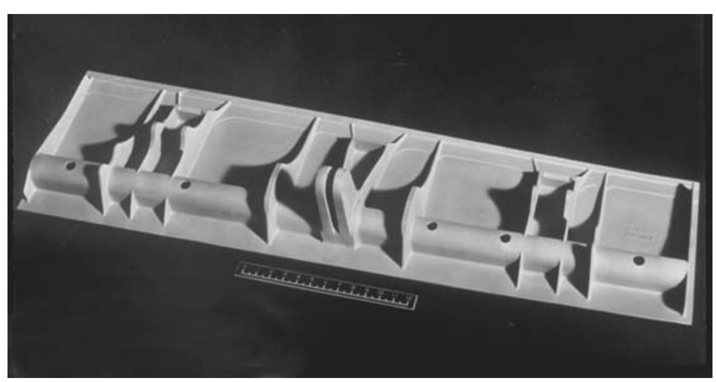

Fig. 3.18 Premium engineered casting aircraft wing flap

3.7.7 Aluminum-Silicon Eutectic Modification and Grain Refinement

The use of chemical modifiers in hypoeutectic aluminum-silicon alloys has been the subject of ongoing research. Beneficial effects on solidification, feeding, and properties are well established. Research has included the effects of a large number of elements and element combinations on eutectic and phase structures. The most potent modifier, sodium, has been extensively used in all gravity casting operations. The advantageous interaction of sodium and strontium was also recognized and became the basis for the use of both elements in modification additions.

For premium engineered castings, the artifacts of modifier additions—notably increased hydrogen solubility and the introduction of large amounts of hydrogen by alloying methods—made eutectic modification counterproductive for most premium engineered castings. Casting results for rapidly solidified unmodified castings proved superior to those of chemically modified, less-sound castings produced under the same conditions.

At one time, essentially uncontrolled titanium additions were routinely made for grain refinement. Extensive studies of the ratios of titanium and boron and their intermetallic forms most effective for grain refining resulted in rapid advances in foundry practice. Later studies would provide new insights that continuously redefined the advanced standards and procedures for grain structure control in premium engineered casting production.

3.7.8 Mold Filling

The inevitable degradation of melt quality that occurs in drawing and pouring through conventional methods was recognized as a significant barrier to achieving premium engineered quality levels and properties. Very significant efforts had been made to evaluate different pouring and gating approaches. These included siphon ladles, sprue/gate/runner ratios, runner overruns, dross traps, pouring cup designs, strainers and screens, and nonvortexing cross-sectional geometry of downsprues and runners. The use of optimal gating designs and rigorously controlled practices are integral components of premium casting technology.

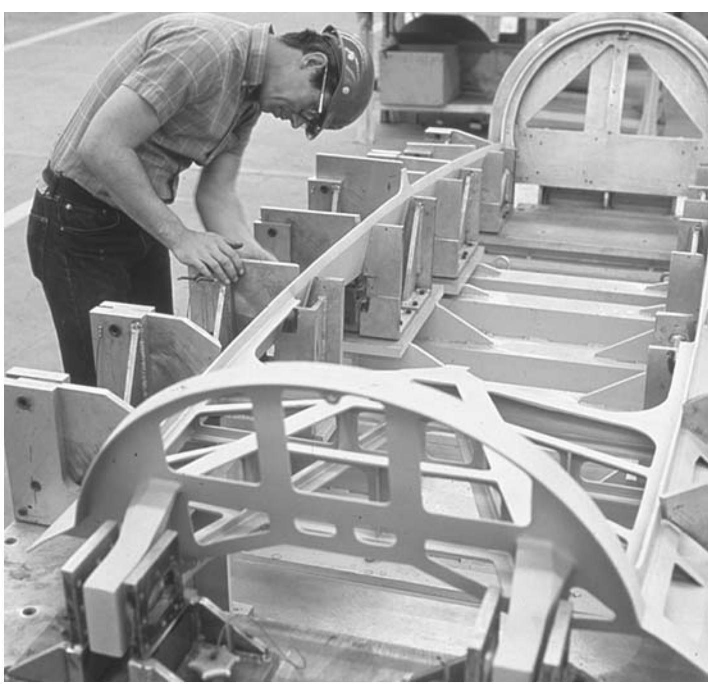

Fig. 3.19 Premium engineered casting aircraft canopy

Several developments have altered mold-filling options; these developments are described in the following paragraphs.

First, the low-pressure casting process achieved commercial importance in the United States in the 1950s. A number of challenges that were unaddressed by commercial low-pressure systems were successfully met. A cam-controlled back-pressure method based on gross casting weight was used to retain residual metal levels at the top of the feed tube. This feature prevented the inclusion spawning characteristic of normal low-pressure cycles. In-gate filtration and screening methods were also devised.

The range of part designs and alloys that were cast would be considered unusual today when the low-pressure process has become principally known for automotive wheel production. Instead, the low-pressure method was considered a means of nonturbulent mold filling with a number of additional advantages that included reduced gross/net weight and lower pouring temperature. Some examples were diesel engine and compressor pistons, air-conditioner compressor bodies, bearings, furniture parts, and missile fins. Geometric symmetry, which is normally a criterion for low-pressure production was not considered a prerequisite, and many of the castings that were produced used conventional risering rather than exclusively relying on the in-feed for shrinkage compensation.

These developments were adapted to premium engineered plaster and dry sand parts. High-speed rotors and impellers were excellent examples, but many other premium engineered casting configurations were made by low-pressure mold filling.

Second, countergravity mold-filling methods were developed involving the use of mechanical or induction pumps.

Third, various techniques have been developed and are in use for filling molds quiescently by displacement of molten metal.

Fourth, solidification time was not a significant factor in expendable mold production when extensive chilling was used, but it was always a factor in permanent mold. For this reason, and to overcome other low-pressure process limitations, vacuum riserless casting (VRC) was developed in the early 1960s. Rather than pressurize a contained molten reservoir, the application of a vacuum on the mold cavity drew metal from the bath through a short fill tube. The metal source was exposed for periodic treatment, the distance from subsurface metal entry to the casting cavity was minimal, dies were extensively chilled, and the process could be highly automated. While only relatively small and simple shapes were produced by the VRC method, productivity and mechanical properties were exceptional. More than 20 million air-conditioner pistons and millions of rocker arms were produced by this process.

Fifth, the level pour process for premium engineered castings was developed. This process had its origins in the direct chill process that was developed for fabricating ingot. It was natural that the shared concerns for metal distribution and solidification principles would result in the synthesis of process concepts.

Aluminum-tin alloy bearings, which were typically hollow or solid cylinders, could be produced by the direct chill process, but

segregation and safety concerns led to a variation in which metal was introduced to the bottom of a permanent mold through a moving pouring cup that traversed the length of the mold. Quiescent flow and the continuous layering of molten metal provided improved internal quality. Excellent soundness was obtained without the use of the extensive risering normally required for these long solidification range alloys, pouring temperature was reduced, and the solidified structure was more chemically homogeneous than in conventionally cast parts.

With determined engineering, the same approach was successfully used for more complex configurations with more challenging metallurgical requirements. The cost of doing so in permanent mold was not typically justified. However, aircraft and aerospace parts in the limited quantities normally associated with sand casting offered exciting opportunities for level pour technology, and a large number of prototype and production parts were produced by this method. In its final form, the assembled mold was lowered on a hydraulic platform through a trough arrangement that provided nonturbulent flow of metal through entry points that paralleled the vertical traverse of the mold. Metal flow was controlled by the dimensions of the entries and the lowering rate, which could be modulated for cross-sectional variations as a function of mold travel. Characteristic of the direct chill process on which it was based, the level pour process features quiescent molten metal flow, minimized feeding distances, and reduced pouring temperatures.

3.7.9 Quality Assurance

The production of premium engineered castings involves extensive nondestructive evaluation and certification. Acceptance usually requires radiographic examination, fluorescent penetrant inspection, and dimensional verification. Mechanical properties are often determined in destructive tests, usually involving machined subsize specimens taken from designated areas of randomly selected castings.

Practices developed for first article qualification must be meticulously defined, and specification restrictions and requalification procedures are imposed on changes or modifications. In some cases, the practices must be disclosed and in others may remain proprietary. Confirmation that practices have been observed may take the form of furnace and heat treatment records, for example, by government and/or customer on-site inspectors. Another possibility is that these records may become part of the certification process in which inspection records, mechanical property test results, and radiographic film are submitted with the castings.

The objective of premium engineered casting is the ultimate development of material properties, consistency, and performance. The pioneering developments of these efforts have been continuously refined, and today a number of foundries demonstrate the unique capabilities for meeting the exacting standards that are required.

3.7.10 Relevance of Premium Casting Engineering

Just as technologies developed in the space program have found applications in industry, premium engineered casting developments have important implications for all aluminum foundries. The principles and processes of premium casting can be cost effectively applied to conventional aluminum casting production.

From the applications standpoint, strength, ductility, and other mechanical attributes are only equal in importance to reliability. Variability in soundness and performance remains the greatest concern in engineered structural applications for which castings compete. The processes and controls for narrowing material variations in premium engineered castings form part of the basis for aggressive cooperative materials development programs in automotive and aerospace applications that emphasize process capabilities rather than reliance on nondestructive evaluation. No premium engineered castings foundry could survive the inspection losses if the process was not capable of consistently meeting specified requirements. No commercial foundry can expect to remain competitive if the casting process cannot deliver consistent quality with minimum internal and external losses without reliance on expensive and time-consuming nondestructive testing.

The goal of reducing product variability and the consistent achievement of specified product characteristics through the selected use of processes and controls developed for premium engineered castings is within the range of capability for all aluminum foundries and for the fullest range of casting types and specifications.

3.8 Other Process Technologies

Other process technologies of importance for aluminum alloy castings that affect properties and performance are:

- Metallurgical bonding
- Metal-matrix composites (MMCs)
- Hot isostatic pressure

3.8.1 Metallurgical Bonding

It is possible to mechanically or metallurgically bond dissimilar metals in aluminum casting.

The Al-Fin Process results in a continuous metallurgical structure from the insert through an intermetallic boundary to the base alloy of the casting. While inserts can be simply placed in the mold before pouring to form a mechanical union between the two materials, the union is dependent only on the intimacy of contact and the force exerted by differences in thermal contraction characteristics. Copper, ferrous, and other alloy components such as cast-in cooling coils and piston wrist pin struts become integral to the cast structure.

By preimmersing inserts in molten aluminum so that an intermetallic layer is developed by chemical attack, the insert rapidly placed in the mold can be metallurgically rather than mechanically bonded to the cast aluminum structure.

Compression ring groove inserts in diesel engine pistons and the bearing surfaces of rotating parts are often metallurgically bonded to ensure structural integrity, strength, and heat transfer. Various iron grades, steel, and stainless steel elements have been successfully and routinely bonded to aluminum casting structures. High nickel iron and steel offer advantages in the similarity of expansion coefficients so that stresses through operating temperature ranges are reduced.

Preimmersion baths of aluminum-silicon alloys provide uniform thin intermetallic layers with minimal residual retention of bath when inserts are transferred to the mold. Since iron is continuously dissolved, the bath must be periodically discarded or diluted to prevent the deposition of iron containing insoluble phases on the insert surface.

Because the insert must be positioned, the mold closed and poured before the aluminum residual to the insert surface solidifies, bonding is typically performed in permanent molds.

3.8.2 Cast Aluminum-Matrix Composites

Incorporating particles or fibers of dissimilar materials in cast aluminum structures substantially alters material properties. Ceramics, graphite, alumina, silicon carbide, other carbides, and nitrides wet by molten aluminum form a reinforced structure typically displaying substantially increased modulus of elasticity, higher strength, and improved wear resistance. While tensile strengths in excess of 100 ksi (700 MPa) can be achieved, the characteristic ductility of composite structures is limited.

Powder metallurgy composites are commercially important, and there is a growing technical capability and market for cast aluminum metal-matrix composite parts. Cast composites offer cost-advantaged near-net-shape capabilities in sizes and configurations not achievable in powder metallurgy or by other forming methods with the same advantages in exceptional specific stiffness (elastic modulus-to-weight ratio), strength, wear resistance, and the option of selectively reinforcing or altering local material properties.

Most cast MMC parts are produced from prealloyed/mixed alloy in conventional casting processes. Mechanical or other forms of agitation are employed to maintain the homogeneous suspension of particulate after melting. The segregation of density-differentiated particles in aluminum is strongly influenced by particle size and time. If the dispersion can be maintained through melting, holding, and mold filling, more rapid solidification characterized by permanent mold and die casting promotes the more uniform distribution of particles in the solidified structure.

Recent developments concern increasingly fine particle sizes to nanodimensions and shapes such as fibrules and microspheres, which will result in a reduced tendency for density segregation before and during solidification. Finer particulate distribution has also shown improvements in ductile behavior while preserving advantages in stiffness and strength. Another notable development involves the use of low-cost particulate such as represented by industrial waste materials such as fly ash to produce low-density, property-enhanced parts with reduced material costs.

The most important castable aluminum-base MMC compositions originate in conventional alloys to which from 10 to 20 vol% particulate silicon carbide (SiC), alumina, or other ceramic material has been added. Particle wetting and distribution are functions of ingot production or of procedures used during melting and blending. Composite ingots are remelted, uniform dispersion of particulate is mechanically or inductively ensured, and casting is accomplished using conventional foundry practices and equipment. The fluidity and flow characteristics of composite alloys are not significantly different from those of conventional unreinforced alloys so that mold designs and gating systems of routine production can be successfully used. Production parts have been cast in sand, permanent mold, pressure die, and investment processes.

Metal-matrix composites are also cast by impregnation of fiber cake in gravity and squeeze casting processes. Impregnated cast composites begin with a permeable ceramic cake formed to comprise a section of the casting to be reinforced. The cake is intruded to obtain the composite structure.

Recent alternative developments involving matrix reinforcement concepts include the investigation of postsolidification surface treatments including flame and plasma spray deposition, and high-intensity infrared and plasma heating of ceramic overlays.

Typically, MMC scrap cannot be recovered except by separation of the composite component.

Existing or emerging applications for cast aluminum composites are:

- Brake rotors (Fig. 3.20)
- Cylinder liners (Fig. 3.21)
- Power-steering pulleys
- Connecting rods

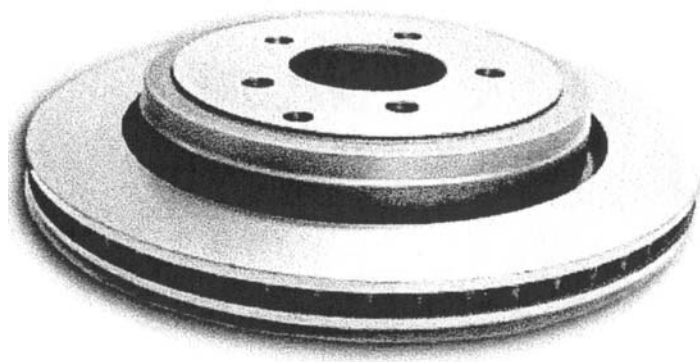

Fig. 3.20 Alloy 359/SiC/20p metal-matrix composite brake rotor. Source: Ref 6

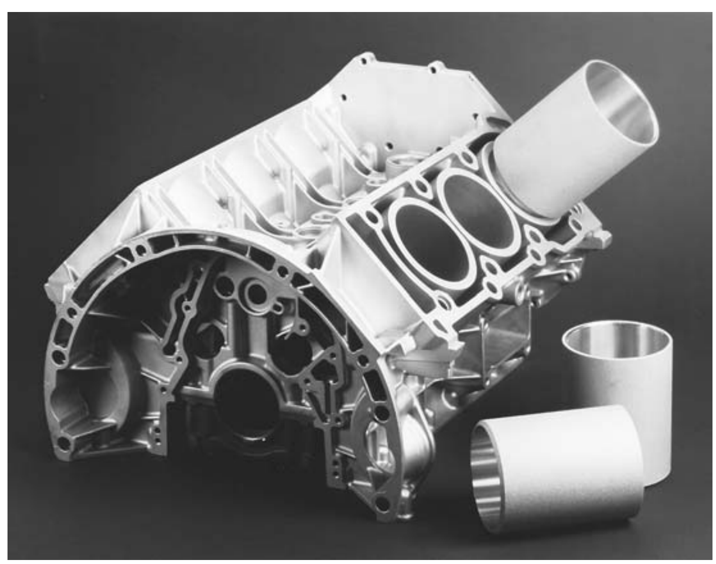

Fig. 3.21 Metal-matrix composite (MMC) cylinder liners. The MMC offers an alternative to cast iron or hypereutectic aluminum-silicon alloy for this application.

- Bicycle frames
- Scraper blades and shoes
- Sporting equipment
- Golf club heads
- Aerospace optical systems
- Electronic/avionic thermal management components
- Pressure vessels
- Brackets
- Wave guides

3.8.3 Hot Isostatic Pressing (HIP)

The application of hot isostatic pressing (HIP) to aluminum alloys following casting is a key technology for improving properties by reducing or eliminating the effects of porosity and inclusions. This technology is sufficiently important that it is covered in a separate chapter (Chapter 6), following the discussion of the nature and cause of such imperfections.

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CHAPTER 4

The Effects of Microstructure on Properties

Microstructural features are products of metal chemistry and solidification conditions. The microstructural features, excluding defects, that most strongly affect mechanical properties are:

- Size, form, and distribution of intermetallic phases
- Dendrite arm spacing
- Grain size and shape
- Eutectic modification and primary phase refinement

4.1 Intermetallic Phases

Controlling element concentrations and observing stoichiometric ratios required for intermetallic phase formation results in preferred microstructures for property development. Solidification rate and the rate of postsolidification cooling promote uniform size and distribution of intermetallics and influence their morphology. Slower rates of solidification result in coarse intermetallics and second-phase concentrations at grain boundaries. Phase formation is diffusion controlled so that more rapid solidification and more rapid cooling to room temperature from solidification temperature results in greater degrees of retained solid solution and finer dispersions of smaller constituent particles.

4.2 Dendrite Arm Spacing

In all commercial processes, with the exception of semisolid forming, solidification takes place through the formation of dendrites from liquid solution. The cells contained within the dendrite structure correspond to the dimensions separating the arms of primary and secondary dendrites and are exclusively controlled for a given composition by solidification rate (Fig. 4.1).

There are at least three measurements used to describe dendrite refinement:

- *Dendrite arm spacing:* The distance between developed secondary dendrite arms
- *Dendrite cell interval:* The distance between centerlines of adjacent dendrite cells
- *Dendrite cell size:* The width of individual dendrite cells

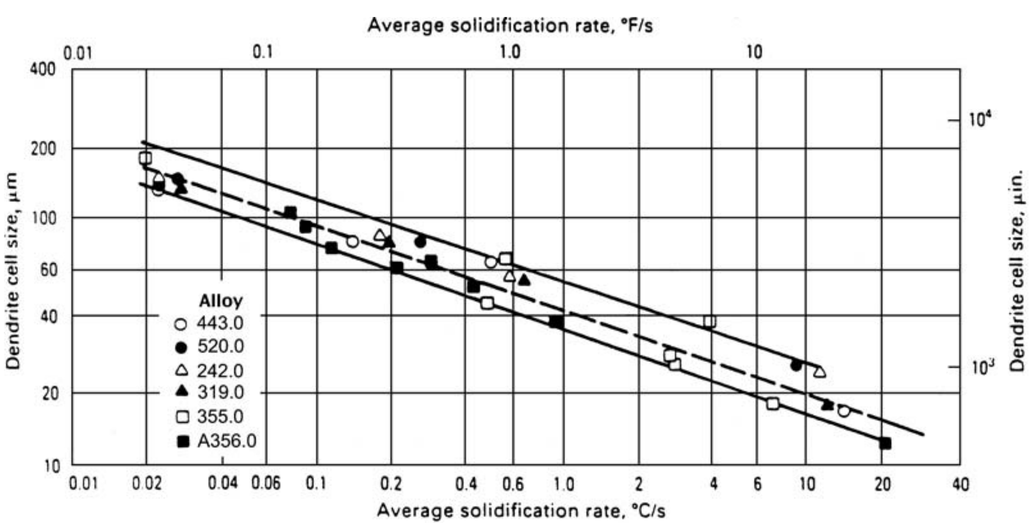


Fig. 4.1 Dendrite arm spacing and dendrite cell size as a function of local solidification rate. Source: Ref 1

The larger the dendrite arm spacing, the coarser the microconstituents and the more pronounced their effects on properties. Finer dendrite arm spacing is desirable for improved mechanical property performance (Fig. 4.2, 4.3) (Ref 2).

Cooling rates directly control dendrite arm spacing, which influences property development and substantially improves ductility:

	Cooling rate		Dendrite arm spacing	
Casting processes	°F/s	°C/s	mils	μm
Plaster, investment	1.80	1	3.94–39.4	100–1000
Green sand, shell	18.0	10	1.97–19.7	50–500
Permanent mold	180.0	100	1.18–2.76	30–70
Die	1800	1000	0.20–0.59	5–15

4.3 Grain Refinement

Fine, equiaxed grains are desired for the best combination of strength and ductility by maximizing grain-boundary surface area and more finely distributing grain-boundary constituents (Ref 3). Coarse grain structure and columnar and feather or twin-columnar grains that form with high thermal gradients in low-alloy-content compositions are by comparison detrimental to mechanical properties. The type and size of grains formed are functions of alloy composition, solidification rate, and the concentration of effective grain nucleation sites.

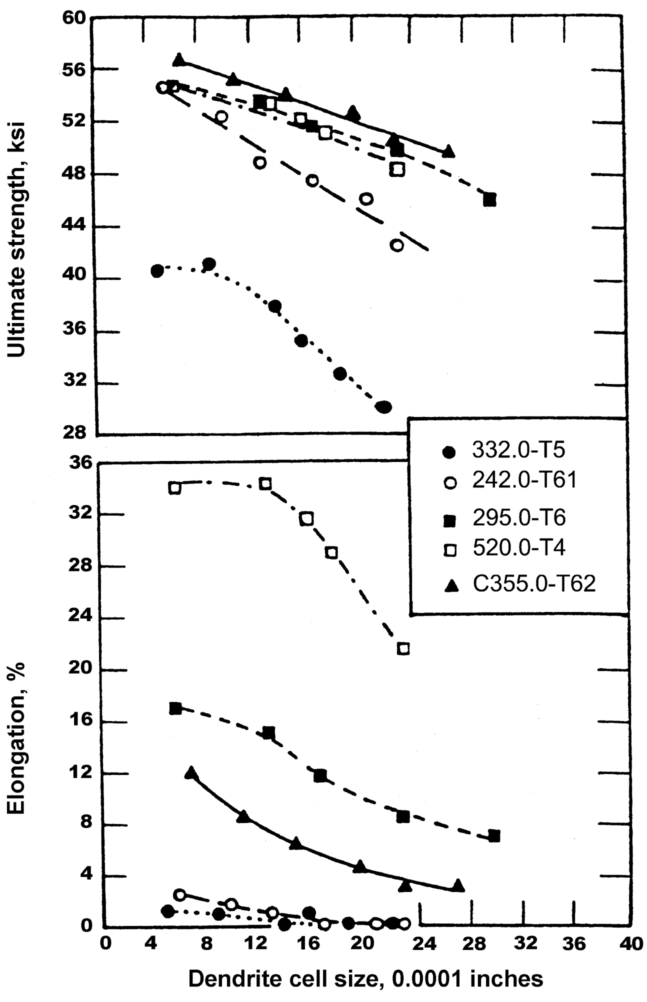


Fig. 4.2 Dendrite cell size effects on the strength and elongation of several aluminum casting alloys. Source: Ref 1

Increased solidification rate reduces grain size (Ref 4), but solidification rates in complex cast structures typically vary and the degree of grain refinement practically achievable in commercial gravity casting processes is lower than that obtained by effective heterogeneous nucleation through grain-refiner additions before casting (Fig. 4.4).

All aluminum alloys can be made to solidify with a fully equiaxed, fine-grain structure through the use of suitable grain-refining additions (Ref 5, 6). The most widely used are master alloys of titanium or of titanium and boron. Aluminum-titanium refiners generally contain from 3 to 10% Ti. The same range of titanium concentrations is used in Al-Ti-B refiners with boron contents from 0.2 to 1% and titanium-to-boron ratios ranging from 5 to 50. Selected carbides also serve grain-refining purposes in aluminum alloys (Ref 7).

Although grain refiners of these types can be considered conventional hardeners or master alloys, they differ from true master alloys added to the melt exclusively for alloying purposes. To be effective, grain refiners must introduce controlled, predictable, and operative quantities of aluminides and borides or carbides in the correct form, size, and distribution for grain nucleation. Refiners in rod form, developed for the continuous treatment of aluminum in primary operations and displaying clean, fine, unagglomerated microstructures, are available in sheared lengths for foundry use. In addition to grain-refining master alloys in waffle or rolled rod form, salts, usually in compacted form that react with molten aluminum to form combinations of $TiAl_3$ and TiB_2, are also available.

Transduced ultrasonic energy has been shown to provide degrees of grain refinement under laboratory conditions (Ref 8, 9). No commercial use of this technology has been demonstrated. The application of this method to engineered castings is problematic.

4.4 Aluminum-Silicon Eutectic Modification

The properties of hypoeutectic aluminum-silicon alloys can be affected by modifying the form of the eutectic. A finer, more fibrous eutectic structure can be obtained by increased solidification rate and by the addition of chemical modifiers. Calcium, sodium, strontium, and antimony are known to influence the degree of eutectic modification that can be achieved during solidification. Figure 4.5 illustrates variations in degree of modification achieved by modifier additions.

Sodium is arguably the most potent modifier, but its effects are transient because of oxidation and vapor pressure losses. Strontium is less transient but may be less effective for modification under slow solidification rates (Fig. 4.6).

The combination of sodium and strontium offers advantages in initial effectiveness. Calcium is a weak modifier with little commercial value. Antimony provides a sustained effect, although the result is a finer lamellar rather than fibrous eutectic. The effects of sodium, strontium, and Na + Sr on modification are shown in Fig. 4.6 and 4.7.

The addition of metallic sodium to molten aluminum creates turbulence that can result in increased hydrogen and entrained oxide levels. The use of hygroscopic salts including NaCl and NaF for modification also risks oxide formation and increased dissolved hydrogen content. Postaddition fluxing to restore melt quality increases the rate of sodium losses. The excessive use of sodium (>0.01 wt%) increases misrun tendencies through increases in surface tension and diminished fluidity.

Strontium additions are usually made through master alloys containing up to 10% of the modifier. While these additions are made with minimum melt degradation, strontium is associated with an increased tendency for hydrogen porosity, either through increasing hydrogen solubility or decreased surface tension.

The greatest benefits of eutectic aluminum-silicon modification are achieved in alloys containing from 5% Si to the eutectic concentration. The addition of modifying elements to these alloys results in a finer lamellar or fibrous eutectic structure. The modifying additions either suppress the growth of silicon crystals within the eutectic or equilibrate silicon-matrix growth rates, providing finer lamellae.

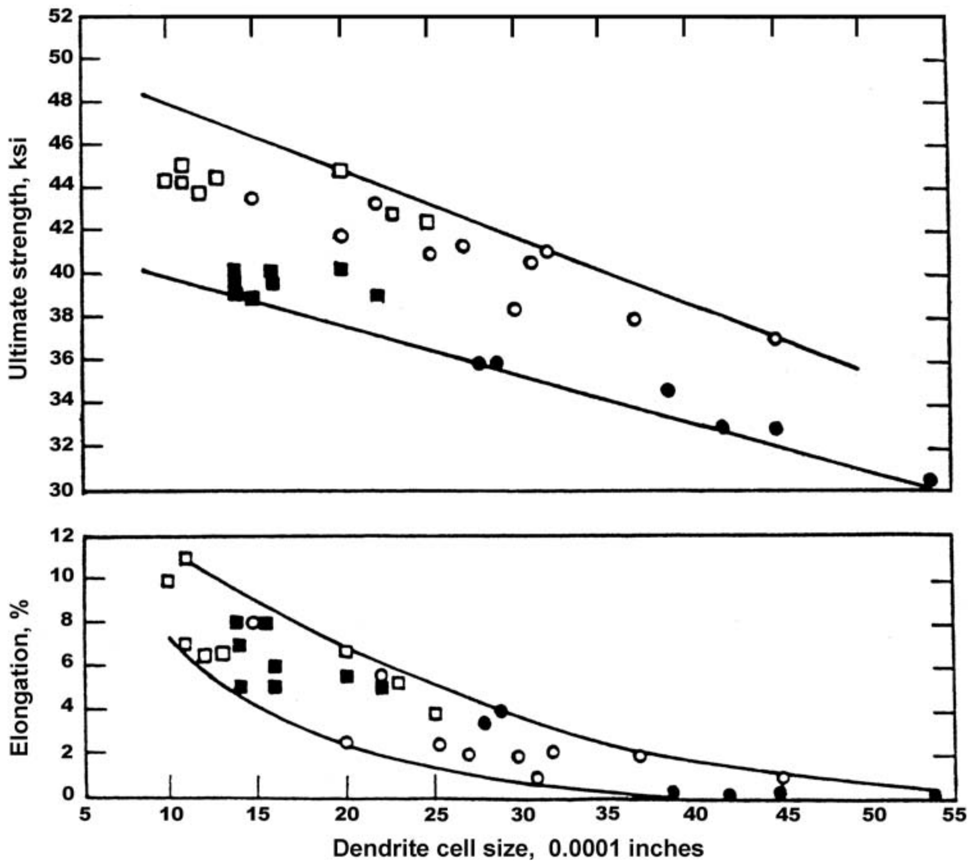
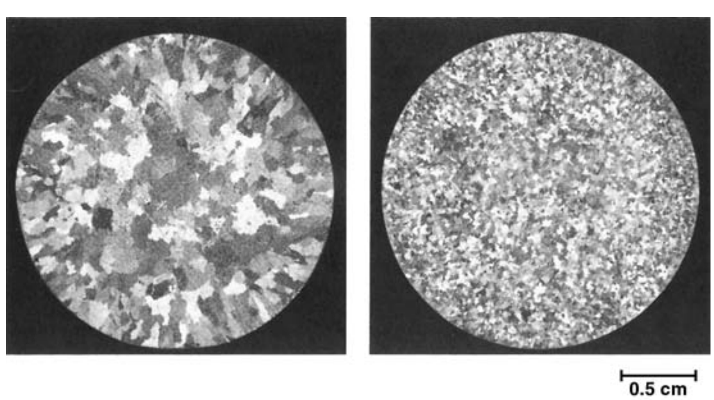


Fig. 4.3 Correlation between dendrite cell size and tensile properties of specimens machined from production castings in alloy A356.0-T62. The different data points indicate specimens from different heats. Source: Ref 1



(a) (b)

Fig. 4.4 As-cast Al-7Si ingots showing the effects of grain refinement. (a) No grain refiner. (b) Grain refined. Both etched using Poulton's etch; both 2×. Courtesy of W.G. Lidman, KB Alloys Inc.

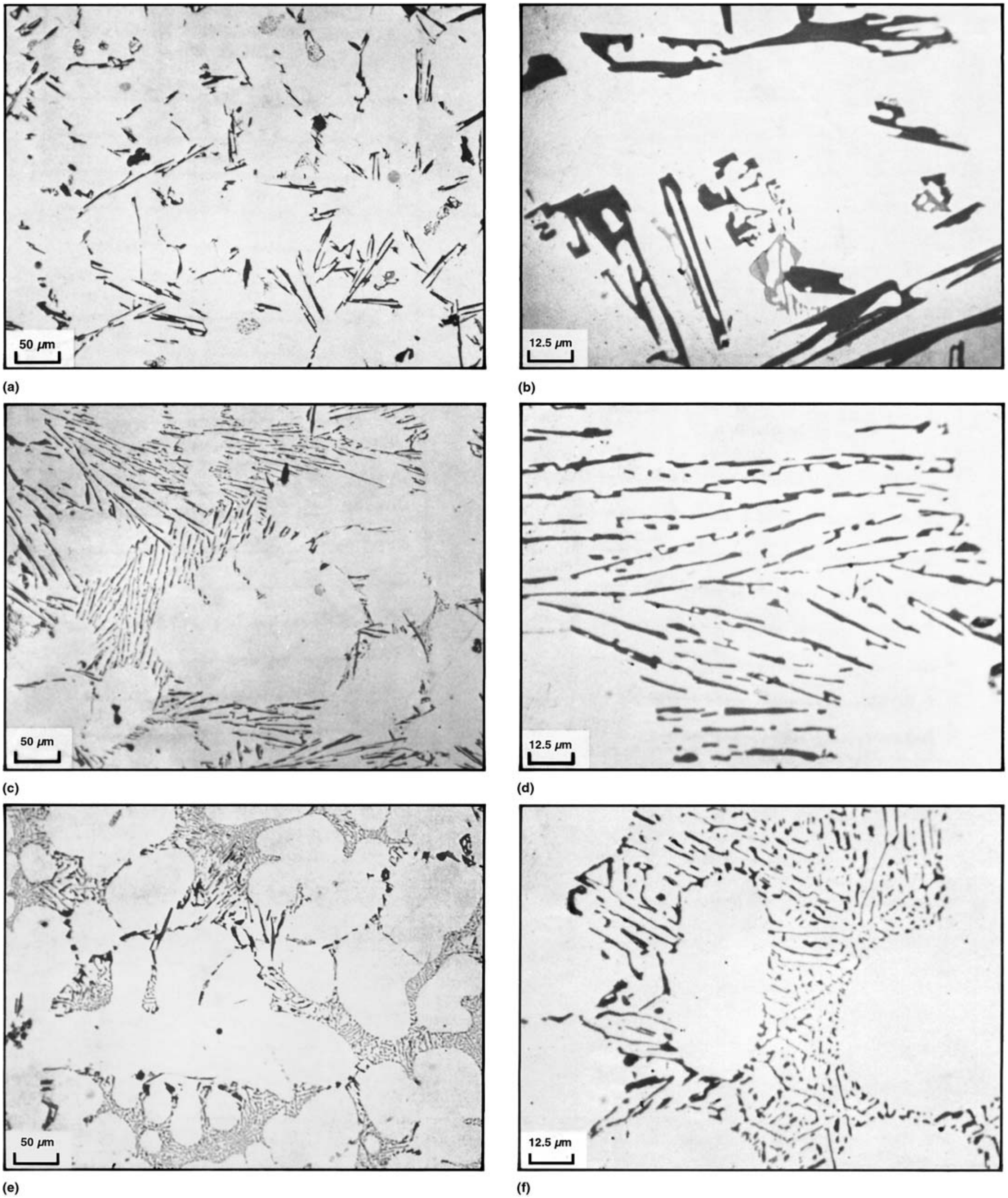
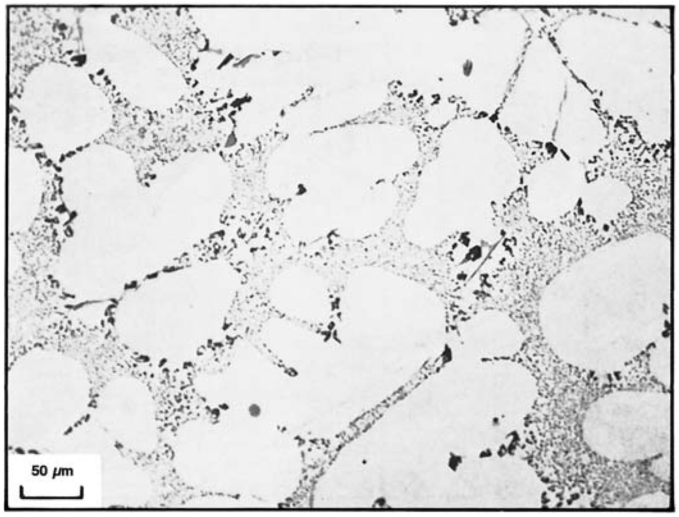
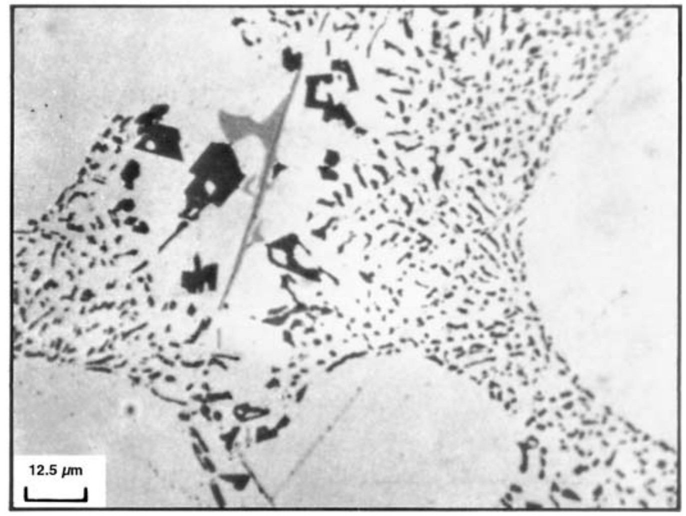


Fig. 4.5 Variations in degrees and types of aluminum-silicon eutectic modification. (a) Class 1, fully unmodified structure. 200×. (b) Same as (a) but at 800×. (c) Class 2, lamellar structure. 200×. (d) Same as (c) but at 800×. (e) Class 3, partial modification. 200×. (f) Same as (e) but at 800×. (g) Class 4, absence of lamellar structure. 200×. (h) Same as (g) but at 800×. (i) Class 5, fibrous silicon eutectic. 200×. (j) Same as (i) but at 800×. (k) Class 6, very fine structure. 200×. (l) Same as (k) but at 800×. Source: Ref 10



(g)



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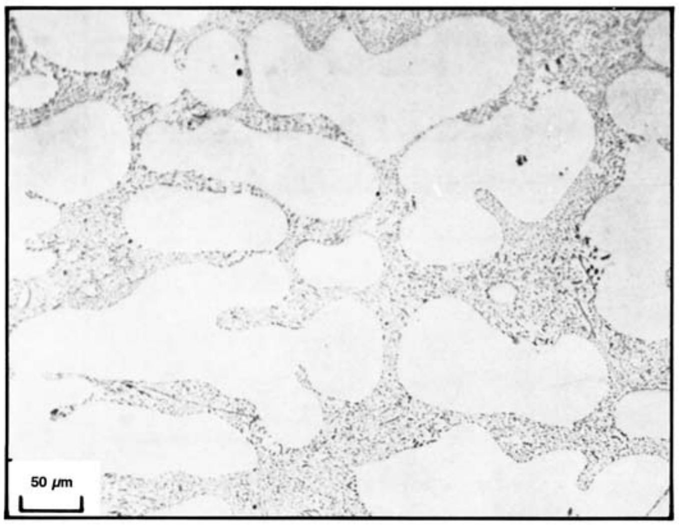
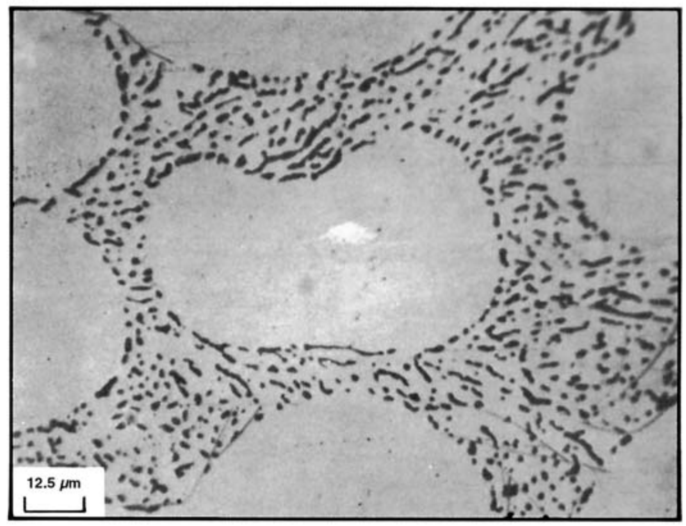


(i)



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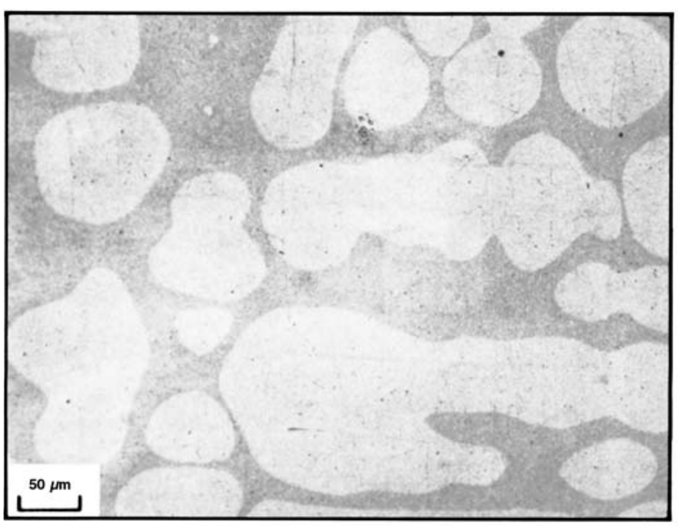
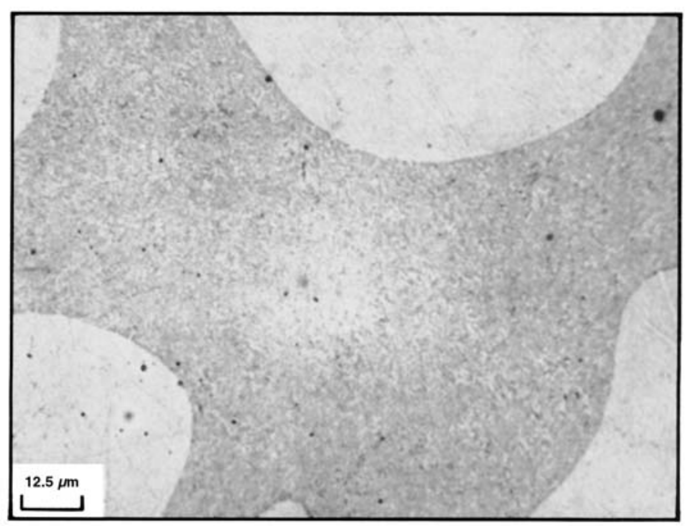


(k)



(l)

Fig. 4.5 (continued) (g) Class 4, absence of lamellar structure. 200×. (h) Same as (g) but at 800×. (i) Class 5, fibrous silicon eutectic. 200×. (j) Same as (i) but at 800×. (k) Class 6, very fine structure. 200×. (l) Same as (k) but at 800×. Source: Ref 10

Phosphorus interferes with the modification mechanism. It reacts to form phosphides that nullify the effectiveness of modifier additions. It is therefore desirable to use low-phosphorus metal when modification is a process objective and to make larger modifier additions to compensate for phosphorus-related losses.

Typically, modified structures display higher tensile properties and appreciably improved ductility when compared to unmodified structures (Table 4.1). Property improvement is dependent on the degree to which porosity associated with the addition of modifiers is suppressed. Improved casting results include improved feeding and superior resistance to elevated-temperature cracking.

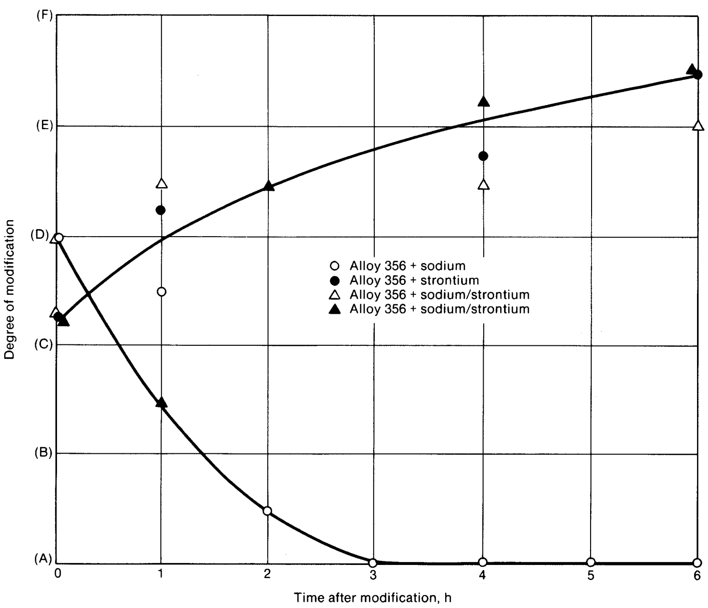


Fig. 4.6 Effectiveness of sodium and strontium modifiers as a function of time. See Fig. 4.7 for degrees of modification

Thermal analysis is useful in assessing the degree of modification that can be displayed by the melt (Ref 11). A sample of metal

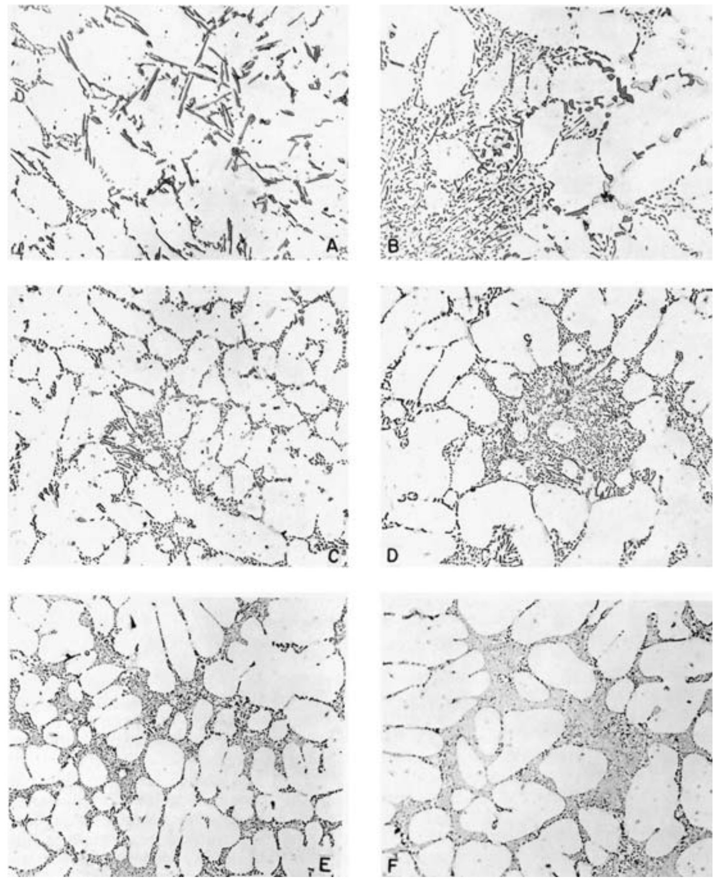


Fig. 4.7 Varying degrees of aluminum-silicon eutectic modification ranging from unmodified (A) to well modified (F). See Fig. 4.6 for the effectiveness of various modifiers

Table 4.1 Typical mechanical properties of modified and unmodified cast aluminum alloys

Alloy and temper	Product	Modification treatment	Tensile yield strength, ksi	Tensile yield strength, MPa	Ultimate tensile strength, ksi	Ultimate tensile strength, MPa	Elongation, %
13% Si	Sand cast test bars	None	...	...	18.0	124	2.0
		Na-modified	...	...	28.0	193	13.0
	Permanent mold test bars	None	...	...	28.0	193	3.6
		Na-modified	...	...	32.0	221	8.0
359.0	Permanent mold test bars	None	...	...	26.1	180	5.5
		0.07% Sr	...	...	30.5	210	12.0
356.0-T6	Sand cast test bars	None	30.1	208	41.9	289	2.0
		0.07% Sr	34.5	238	42.5	293	3.0
	Bars cut from chilled sand casting	None	30.9	213	41.2	284	4.4
		0.07% Sr	31.6	218	42.2	291	7.2
A356.0-T6	Sand cast test bars	None	26.0	179	40.0	226	4.8
		0.01% Sr	30.0	207	43.0	297	8.0
A444.0-T4	Permanent mold test bars	None	...	...	21.9	151	24.0
		0.07% Sr	...	...	21.6	149	30.0
A413.2	Sand cast test bars	None	16.3	112	19.8	137	1.8
		0.005–0.05% Sr	15.6	108	23.0	159	8.4
	Permanent mold test bars	None	18.1	125	24.4	168	6.0
		0.005–0.08% Sr	18.1	125	27.7	191	12.0
	Test bar cut from auto wheel	0.05% Sr	17.5	121	28.0	193	10.6
		0.06% Sr	18.2	126	28.0	193	12.8

Source: Ref 4

is cooled slowly, permitting time and temperature to be plotted (Fig. 4.8). The effectiveness of modification treatment is defined by the degree and duration of undercooling at the solidus. Test results must be correlated with the degree of modification established metallographically for the castings since cooling rate for the sample will differ.

4.5 Refinement of Hypereutectic Aluminum-Silicon Alloys

The elimination of large, coarse primary silicon crystals that are harmful in the casting and machining of hypereutectic silicon alloy compositions is a function of primary silicon refinement (Ref 13). Phosphorus added to molten alloys containing more than the eutectic concentration of silicon, made in the form of metallic phosphorus or phosphorus-containing compounds such as phosphor-copper and phosphorus pentachloride, has a marked effect on the distribution and form of the primary silicon phase (Fig. 4.9). Retained concentrations of phosphorus as low as 0.0015% are effective in achieving refinement of the primary phase.

Refinement resulting from phosphorus additions can be expected to be less transient than the effects of eutectic modification in hypoeutectic alloys. Phosphorus-treated melts can be solidified and remelted without loss of refinement. Primary silicon particle size increases gradually with time as phosphorus concentration decreases. Gas fluxing accelerates phosphorus loss when chlorine or other reactive gases are used. Brief inert gas fluxing is frequently employed to reactivate aluminum phosphide nuclei, presumably by resuspension.

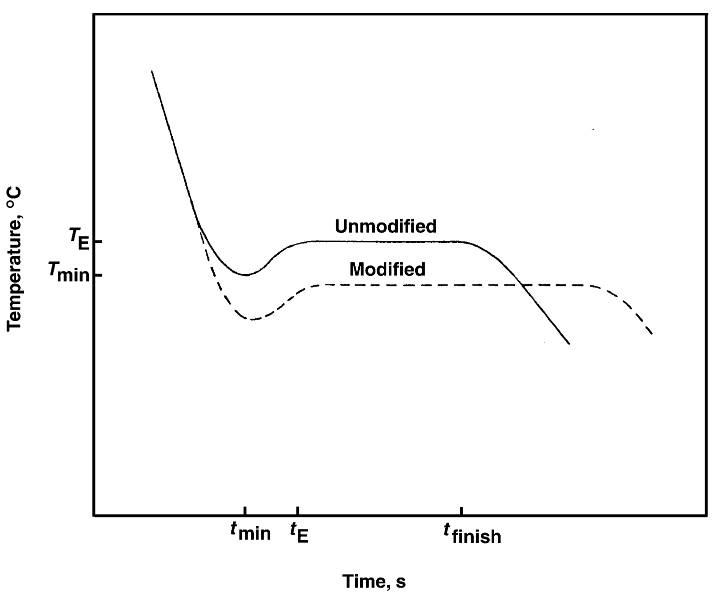


Fig. 4.8 Cooling curve of the eutectic region of an unmodified and modified aluminum-silicon casting alloy. T_{min}, temperature at the minimum before the eutectic plateau; T_E, eutectic growth temperature; t_{min}, time at the minimum of the curve; t_E, time corresponding to the beginning of the eutectic plateau; t_{finish}, time corresponding to the end of the eutectic plateau. Source: Ref 12

Practices recommended for melt refinement are:

- Melting and holding temperature should be minimum.
- Calcium and sodium contents should be controlled to low concentration levels.
- Brief nitrogen or argon fluxing after the addition of phosphorus is recommended to remove the hydrogen introduced during the addition and to distribute the aluminum phosphide nuclei uniformly in the melt.

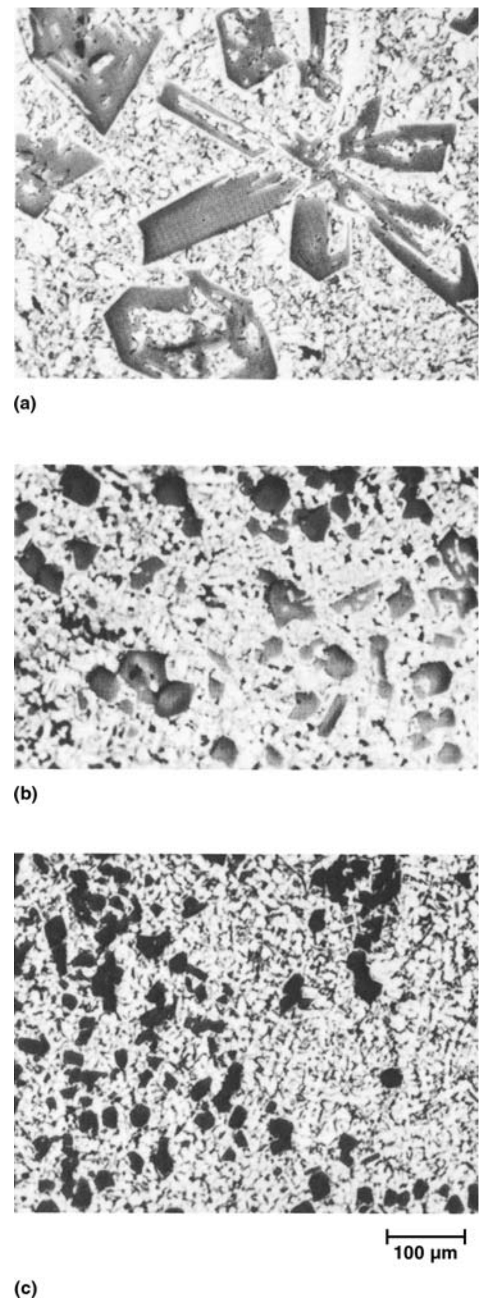


Fig. 4.9 Effect of phosphorus refinement on the microstructure of a hypereutectic Al-22Si-1Ni-1Cu alloy. (a) Unrefined. (b) Phosphorus refined. (c) Refined and fluxed. All 100×

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J.G. Kaufman, E.L. Rooy, p 47-54
DOI:10.1361/aacp2004p047

CHAPTER 5

The Influence and Control of Porosity and Inclusions in Aluminum Castings

Solidification in complex geometrical shapes with varying section thicknesses creates conditions under which internal porosity may form. The impact of internal porosity on properties is caused by the reduction in effective area by pore volume fraction and by stress concentrations at voids leading to premature failure.

Porosity in aluminum is caused by the precipitation of hydrogen from liquid solution or by shrinkage during solidification, and more usually by a combination of these effects. There are other sources of internal voids. Mold reactions, high-temperature oxidation, blowholes, and entrapped gas result in defects that adversely affect mechanical properties as well as physical acceptability.

Nonmetallic inclusions entrained before solidification influence porosity formation and mechanical properties.

5.1 Hydrogen Porosity

Hydrogen is the only gas that is appreciably soluble in aluminum and its alloys. The solubility of hydrogen in aluminum varies directly with temperature and the square root of pressure; solubility increases rapidly with increasing temperature above the liquidus. Hydrogen solubility is considerably greater in the liquid than in the solid state (Fig. 5.1). Actual liquid and solid solubilities in pure aluminum just above and below the solidus are 0.69 and 0.04 ppm. These values vary only slightly for most casting alloys.

The solubility curve for hydrogen in aluminum typically describes equilibrium conditions. No more hydrogen than indicated can be dissolved at any temperature. Control of melting conditions and melt treatment can result in substantially reduced dissolved hydrogen levels.

During cooling and solidification, dissolved hydrogen in excess of the extremely low solid solubility may precipitate in molecular form, resulting in the formation of primary and/or secondary voids. Primary or interdendritic porosity forms when hydrogen contents are sufficiently high that hydrogen is rejected at the solidification front, resulting in supercritical saturation and bubble formation. Secondary (micron-size) porosity occurs when dissolved hydrogen contents are low, and void formation occurs at characteristically subcritical hydrogen concentrations.

Hydrogen bubble formation is strongly resisted by surface tension forces, by increased liquid cooling and solidification rates that affect diffusion, and by an absence of nucleation sites for hydrogen precipitation such as entrained oxides. The precipitation of hydrogen obeys the laws of nucleation and growth and is similar in these respects to the formation of other metallurgical phases during solidification.

The process of hydrogen precipitation consists of:

1. Diffusion of hydrogen atoms within the molten pool
2. Formation of subcritical nuclei as a function of time and cooling
3. Random emergence of stable precipitates that exceed the critical size required for sustained growth
4. Continued growth as long as dissolved hydrogen atoms remain free to diffuse to the precipitated bubble

The result is a general distribution of voids occurring throughout the solidified structure.

Finely distributed hydrogen porosity may not always be undesirable. Hydrogen precipitation may alter the form and distribution of shrinkage porosity in poorly fed parts or part sections. Shrinkage

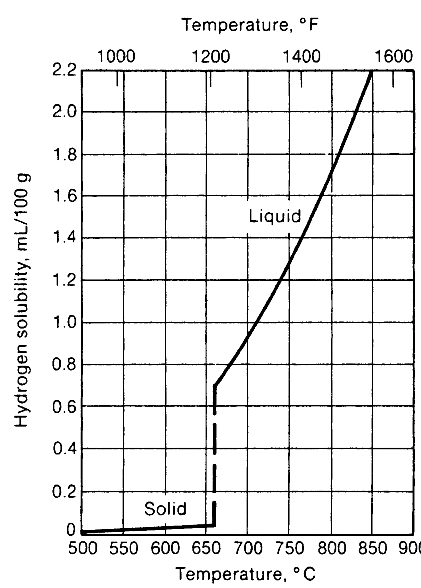

Fig. 5.1 Solubility of hydrogen in aluminum at 1 atm hydrogen pressure

is generally more harmful to casting properties. In isolated cases, hydrogen may be intentionally introduced and controlled in specific concentrations compatible with the application requirements of the casting in order to promote superficial soundness.

The following rules describe the tendency for hydrogen pore formation (Fig.5.2 to 5.5) (Ref 1):

- There is a critical or threshold hydrogen value for any composition that must be exceeded for hydrogen porosity to occur.
- Residual pore volume fraction for each alloy corresponds to hydrogen content above the threshold value.
- Pore volume fraction and pore size decrease with decreased hydrogen content above the threshold value.
- Hydrogen pore volume fraction and pore size decrease with increased cooling rate.

The critical or threshold value of hydrogen concentration is also dependent on pressure and on the number (*n*) and tortuosity (*t*) of liquid paths that exist in a solidifying dendritic network. The higher the product of these factors (*nt*), the higher the hydrogen threshold.

The foundry industry has long used various forms of vacuum testing of molten metal samples to determine acceptability of the processed melt for any casting application. The basis for this test is the relationship between hydrogen solubility and pressure. Since hydrogen solubility is related directly to the square root of pressure, decreased pressure reduces hydrogen solubility, increasing the tendency for bubble formation in the sample. The results of the reduced pressure test can then predict in relative terms the tendency for formation of hydrogen voids in the cast part at ambient pressure. The pressure/solubility relationship recurs in this discussion because of its relevance when negative relative pressures associated with shrinkage develop in the solidifying structure.

Just as in the case of crystal formation, hydrogen precipitation may occur as a result of heterogeneous or homogeneous nucleation. The most powerful nucleants for hydrogen precipitation are oxides, especially oxides that through turbulence in gating, pouring, melt handling, and treatment entrain air or gaseous phases. In the pres-

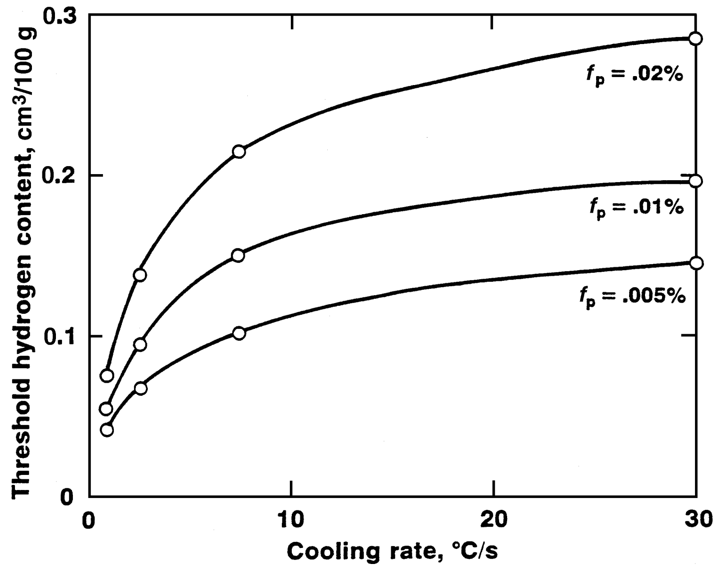

Fig. 5.3 Relationship of hydrogen content to cooling rate in A356.0 for different porosity fractions. f_p, porosity fraction

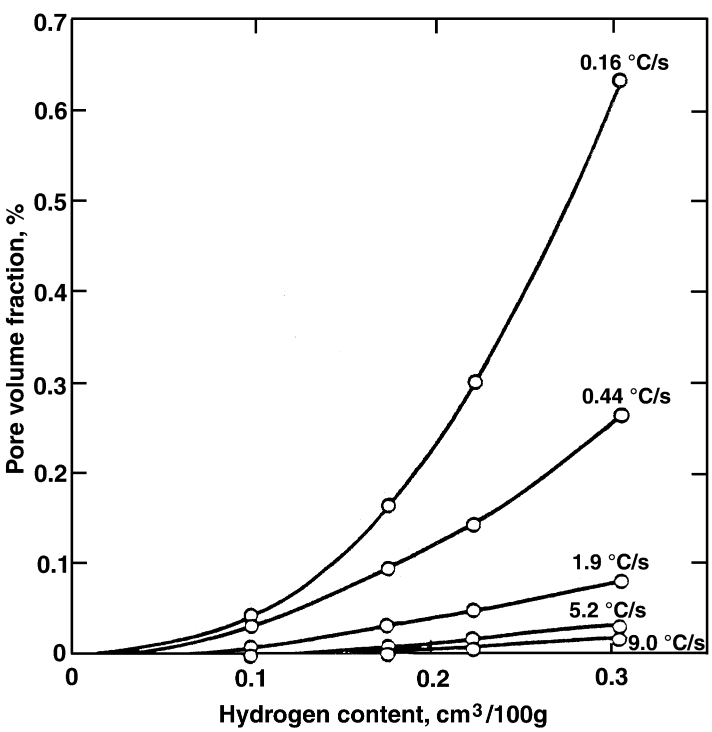

Fig. 5.2 Hydrogen content, pore size, and cooling rate relationships in Al-4Mg alloy

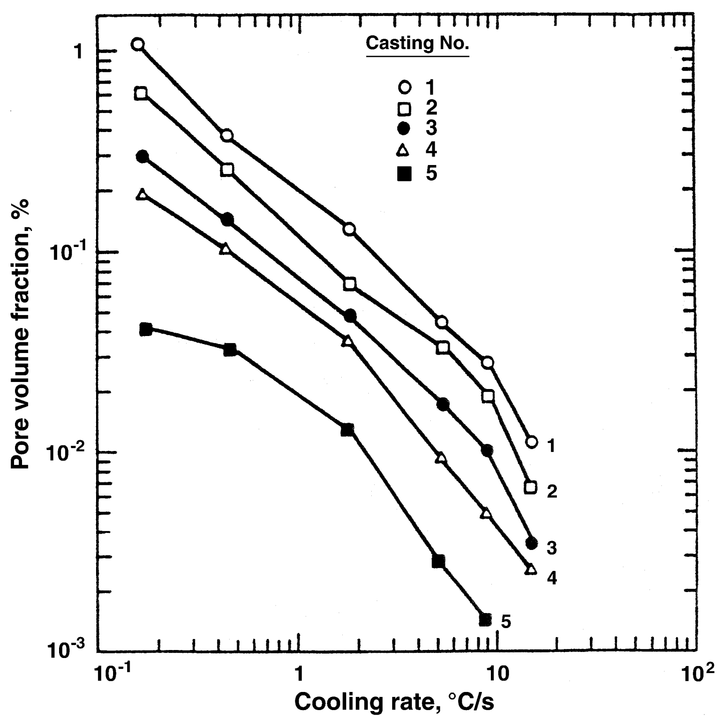

Fig. 5.4 Relationship of pore volume to cooling rate for different hydrogen contents in Al-4.7Mg alloy (similar to alloy 514.0). Hydrogen content (cm³/100 g): 1, 0.31 (no grain refiner); 2, 0.31 (grain refined); 3, 0.22 (grain refined); 4, 0.18 (grain refined); 5, 0.10 (grain refined)

ence of such nuclei, hydrogen precipitates readily at even relatively low dissolved hydrogen levels. In the absence of nucleating phases such as oxides and gaseous species, surface tension forces are generally strong enough that precipitation is suppressed at even relatively high dissolved hydrogen levels. When properly performed, the vacuum solidification test discriminates between bubble formation by heterogeneous and homogeneous nucleation. The determination is made by observing the sample as it cools and solidifies:

- Immediate bubble formation when vacuum is applied indicates that the melt is contaminated by oxides and contains an indeterminate amount of hydrogen.
- Gas evolution appearing in the solidifying sample only during the last stages of solidification indicates that oxides are not present and that hydrogen is present at a relatively high concentration.
- If no evolution of gas occurs, it may be assumed that the melt is free of oxides and that hydrogen contained in liquid solution is below the threshold value for precipitation.

Sources of hydrogen contamination include:

- Atmosphere
- Incompletely dried refractories
- Remelt ingot, master alloys, metallurgical metals, and other charge components
- Fluxes
- Tools, flux tubes, and ladles
- Products of combustion (POCs) in gas-fired furnaces

Hydrogen can be introduced through the disassociation of moisture in the atmosphere and products of combustion in furnace atmospheres allowing atomic hydrogen diffusion into the melt. Turbulence, whether in melt treatment or in pouring can rapidly accelerate the rate at which hydrogen from atmospheric moisture

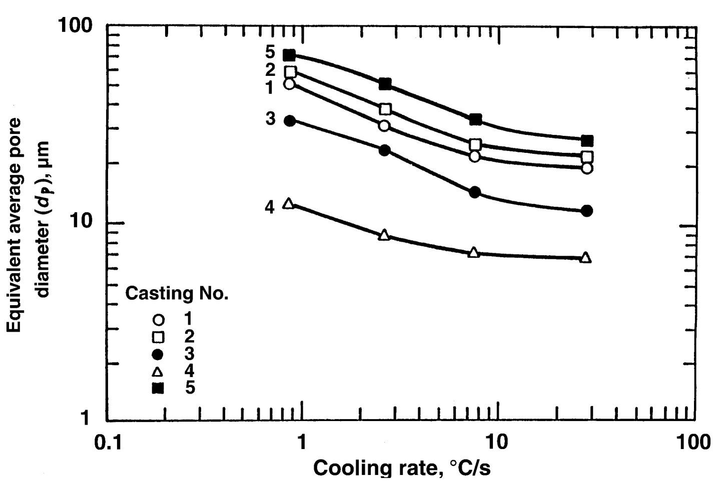

Fig. 5.5 Relationship of pore size to cooling rate for different hydrogen contents in alloy A356.0. Hydrogen content (cm^3/100 g): 1, 0.25 (no grain refiner); 2, 0.31 (grain refined); 3, 0.25 (grain refined); 4, 0.11 (grain refined); 5, 0.31 (grain refined and modified)

is absorbed and coincidentally is responsible for degradation of the liquid melt after effective treatment for hydrogen removal. At any time the protective oxide surface of the melt is disturbed, an increase in hydrogen content can be expected.

In magnesium-containing alloys, an amorphous magnesium oxide forms that is more permeable or less protective to the diffusion of hydrogen from the atmosphere to the melt. It follows that periods of high humidity increase the problems faced in dealing with hydrogen contamination and its removal and that magnesium-containing alloys are more susceptible to hydrogen absorption than others.

Incompletely dried or cured furnace refractories and refractories used to line troughing results in hydrogen absorption.

Dissolved hydrogen is present in some amount in alloyed remelt ingot and master alloys.

Moisture contamination of fluxes and hydrogen in gas fluxes increase hydrogen levels and, in the latter case, affects the efficiency of hydrogen removal.

Moisture in any form: contamination on tools, flux tubes, ingot, scrap, metallurgical metals, grain refiners, and master alloys that may be added to the heat additively affect dissolved hydrogen content up to the applicable solubility limit.

Degassing by the use of inert or active gases reduces hydrogen concentrations by diffusion into bubbles of the fluxing gas corresponding to the partial pressure of hydrogen in the fluxing gas. Spinning-rotor techniques have been developed that provide more intimate mixing, efficient gas-metal reactions, and shorter reaction times to achieve low hydrogen levels. The use of active fluxing gases and filtration removes oxides, permitting acceptable quality castings to be produced from metal with higher hydrogen contents.

5.2 Shrinkage Porosity

For most metals, the transformation from the liquid to the solid state is accompanied by a decrease in volume. In aluminum alloys, the volumetric shrinkage that occurs during solidification ranges from 3.5 to 8.5%. The tendency for the formation of shrinkage porosity is related to both the liquid/solid volume fraction at the time of final solidification and the solidification temperature range of the alloy.

Shrinkage occurs during solidification as a result of volumetric differences between liquid and solid states. It is important to make a distinction between the differences in liquid and solid volume that are of greatest concern to foundry personnel and the contraction that takes place after solidification as a result of solid-state contraction that most concerns die design and patternmaking.

A sphere of molten metal solidifying without risering is an easily understood example of the diverse ways in which shrinkage forms. Once the shell of the sphere has solidified and assumes sufficient strength to resist collapse, the continued process of cooling and solidification results in substantial tensile stresses in the liquid pool since the shell is contracting at the low rate dictated by the solid-state coefficient of thermal contraction, and the volume occupied by the liquid that is cooling and experiencing volume change as additional solid is formed is contracting at a far greater rate. While the liquid struggles to maintain coherency, tensile forces ultimately

exceed surface tension forces associated with the liquid-solid interface and a void will form (Fig. 5.6a). Alloying elements that contribute to elevated-temperature strength such as iron, copper, and nickel increase resistance to surface collapse, leading to contained shrinkage voids. There are variations in which the solidified shell lacks the integrity to resist the negative pressures developed within the sphere. If the shell is coherent, but weak, localized collapse of the shell occurs to compensate for the volumetric change (Fig. 5.6b). Alloys with short solidification ranges often display this form of shrinkage. If localized failure of the shell occurs, interdendritic liquid will drain gravimetrically into the liquid pool that remains (Fig. 5.6c). The result is a "wormhole" or "sponge" shrinkage defect visible from the casting surface. These void concentrations are often associated with cracks that form during and after solidification. Alloys with wide solidification ranges are prone to this form of shrinkage.

In the case of a risered casting, the intention is to prevent shrinkage formation by maintaining a path for fluid flow from the higher heat mass and pressure of the riser to the encased liquid pool.

Shrinkage displacement takes place in three modes:

- Mass feeding
- Interdendritic feeding
- Solid feeding

Mass feeding is liquid displacement occurring in the absence of substantial resistance. In these cases, pressure at the solidification interface and pressure in the riser system are essentially equivalent. Pressure drop develops as obstructions to the feeding path form.

The progressive development of a dendritic network and localized solidification results in increased resistance to fluid flow until the pressure at the solidification front is reduced to zero, at which time a shrinkage void will form. Interdendritic feeding takes place in the interval between mass feeding and the point at which sufficient resistance develops that liquid flow through the solidifying dendrite network no longer occurs.

Solid feeding occurs when the incipient shrinkage void is filled by the collapse of surrounding solidified metal.

Shrinkage may assume many forms. Distributed voids or microshrinkage are found between dendrite arms as a result of failure during the last stages of interdendritic feeding. Centerline or piping voids result from gross directional effects, when, for example, large fully contained liquid pools are isolated within the casting during solidification.

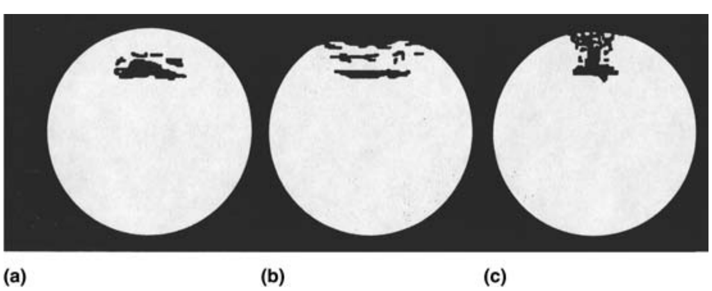

Fig. 5.6 How shrinkage voids form in aluminum castings. (a) Initial void formation. (b) Collapse of shell increases void size. (c) "Wormhole" formation with additional shrinkage

In Al-Si-Cu alloys, rapid cooling leads to the distribution of voids in the grain boundaries, while slow cooling results in interdendritically distributed shrinkage. Shrinkage is much more likely to be localized in a eutectic composition such as 443.0 or A444.0. In any case, voids first begin to form at liquidus-solidus temperatures corresponding to 65 to 75% solid.

In short solidification range compositions such as 356.0 and 413.0, there is an improved opportunity for establishing directional solidification. Defects may take the form of extensive piping as opposed to distributed shrinkage porosity. These alloys may be characterized by a higher proportion of mass feeding relative to interdendritic feeding and are therefore less susceptible, under reasonable efforts to establish directional solidification, to the formation of widely distributed shrinkage voids.

When good foundry practices are used in long solidification range compositions such as some aluminum-copper and aluminum-magnesium alloys, solidification distance loses its importance to a more general tendency for interdendritic shrinkage. These alloys are susceptible to extensive microporosity that results from the higher proportion of feeding that takes place interdendritically. The severity of shrinkage is increased by geometrical complexity, varying section thickness, solidification rate, alloy feeding characteristics, and by limitations in effective gating and risering practice that fail to provide the gradients required for directional solidification.

Shrinkage void fraction varies in proportion to the fourth root of the pressure, leading to the conclusion that increasing pressure has little effect on shrinkage unless extremely high pressures can be employed.

Improved modification and refinement of aluminum-silicon alloys, improved grain refinement, and reduced oxide contents all improve feedability and therefore reduce shrinkage severity.

5.3 Inclusions

Nonmetallic inclusions are a particular concern in cast aluminum. Because of its reactivity, aluminum oxidizes readily in liquid and solid states. Oxidation rate is greater at molten metal temperatures and increases with temperature and time of exposure. Magnesium in aluminum alloys oxidizes and with time and temperature reacts with oxygen and aluminum oxide to form spinel. Table 5.1 categorizes inclusion types typically encountered.

Many oxide forms display densities similar to that of molten aluminum and sizes that reduce the effectiveness of gravimetric separation. Also, most oxides are wet by molten aluminum, reducing the effectiveness of mechanical separation methods.

Aluminum is also chemically aggressive and can react with compounds in refractory formulations or with the coatings used to protect crucibles, ladles, and tools resulting in the entrainment of exogenous nonmetallics.

While the oxide that initially forms on the surface of molten aluminum is highly protective and self-limiting, any agitation or turbulence in the treatment and handling of molten aluminum increases the risk of oxide entrainment and the immediate reformation of additional oxides. Oxide concentration can increase when alloying additions are stirred into the melt, when reactive elements

and compounds are immersed, when metal is drawn for pouring, and when metal is poured and conducted by the gating system into the mold cavity. Induction melting is highly energy efficient and effective for melting fines and poor-quality scrap, but electromagnetically induced eddy currents result in high levels of entrained oxides.

The prevention of inclusions is the product of equipment and practices that minimize oxidation, avoid entrainment, and effectively remove particulate by fluxing reactions or filtration.

Degassing with inert (argon) or quasi-inert (nitrogen) gases are only partially effective in the removal of included matter. Rotary degassing improves inclusion-removal efficiency, but the use of active fluxing gases such as chlorine or other halogens is necessary to dewet included oxides, facilitating their separation by the sweeping action of the fluxing gas. The use of appropriate solid fluxes has the same effect.

Molten aluminum can be filtered by various means with varying effectiveness. Strainers, screens, steel wool, porous foam, and fused ceramics can be used in the gating system as long as the combination of pore size, level of inclusion contamination, and surface area does not excessively restrict metal flow. Cake-mode ceramic and deep-bed filters are used in furnaces and crucibles.

The removal of oxides can be seen to suppress hydrogen pore formation as shown in Table 5.2.

Inclusions occur as varying types with differing sizes and shapes. Aluminum oxides are of different crystallographic or amorphous forms as films, flakes, and agglomerated particles. Magnesium oxide is typically present as fine particulate. Spinels can be small hard nodules or large complex shapes. Aluminum carbide and aluminum nitride can be found in smelted aluminum, but are usually of size and concentration of no significance in aluminum castings. Refractory and other exogenous inclusions may be identified by their appearance and composition.

Inclusions, such as shrinkage and hydrogen porosity, reduce properties by detracting from the effective cross-sectional area when stress is applied and by the concentration of stresses at the inclusion interface (Fig. 5.7).

5.4 Combined Effects of Hydrogen, Shrinkage, and Inclusions

Hydrogen precipitation and shrinkage porosity formation are usually considered separate and independent phenomena. There are interactive mechanisms that affect both.

Small amounts of dissolved hydrogen significantly increase pore size when shrinkage voids form. In this respect, the effects of gas and shrinkage on pore volume fraction can be considered additive.

Since shrinkage voids must by definition result in areas of reduced pressure relative to atmospheric, hydrogen solubility is reduced in the surrounding liquid facilitating the precipitation of hydrogen into the forming void. The important measures of these pores—morphology, pore density, pore size, and volume fraction of pores—are affected by hydrogen.

The conventional wisdom is that hydrogen voids are always rounded, smooth surface defects, while shrinkage voids invariably

Table 5.1 Inclusion sources and types in aluminum alloy castings

Classification	Types observed	Potential source(s)
Nonmetallic exogenous	Various refractory particles, Al_4C_3, etc.	Refractory degradation, remelt ingot, refractory/metal reactions
Nonmetallic in situ	MgO, Al_2O_3 films, clusters, and disperoids; $MgAl_2O_4$ films and clusters	Melting, alloying: metal transfer turbulence
Homogeneous halide salts	$MgCl_2$-NaCl-$CaCl_2$, etc.	Poor separation of fluxing reaction products
Particle/salt	$MgCl_2$-NaCl-$CaCl_2$/MgO, etc.	Salt generated during chlorine fluxing of magnesium-containing alloys, filter and metal-handling system releases

Table 5.2 Effect of filtration on vacuum density test results and hydrogen content

	50 mm Hg vacuum gas test density, g/cm^3		5 mm Hg vacuum gas test density, g/cm^3		Dissolved hydrogen content, mL/100 g	
Test No.	Before filtering	After filtering	Before filtering	After filtering	Before filtering	After filtering
1	2.05	2.67	2.28	2.64	0.76	0.70
2	2.14	2.69	2.45	2.69	0.61	0.69
3	2.16	2.72	2.48	2.70	0.51	0.53
4	2.25	2.78	1.99	2.76	0.38	0.43
5	2.29	2.74	2.07	2.60	0.39	0.38
6	2.24	2.74	1.97	2.71	0.36	0.41
7	2.30	2.73	1.94	2.66	0.31	0.36
8	2.48	2.74	2.27	2.76	0.33	0.31
9	2.34	2.73	2.06	2.61	0.30	0.35
10	2.37	2.73	1.99	2.74	0.30	0.31
11	2.59	2.78	2.29	2.77	0.29	0.27
12	2.58	2.76	2.47	2.76	0.28	0.28
13	2.25	2.74	2.26	2.76	0.27	0.31
14	2.50	2.76	2.13	2.77	0.27	0.28
15	2.62	2.76	2.35	2.78	0.23	0.26
16	2.53	2.73	2.34	2.73	0.28	0.28
17	2.56	2.72	2.32	2.68	0.27	0.32
18	2.19	2.76	2.16	2.76	0.19	0.19

have the characteristic crystalline, jagged appearance that characterizes the dendrite structure. However, hydrogen porosity can conform to dendrite-arm regions, which give bubble formation the characteristic appearance of a shrinkage void. Shrinkage occurring under extremely low gradients may assume a smooth-walled configuration. The precipitation of hydrogen into a forming shrinkage void likewise influences the surface morphology. It is impossible to completely separate the effects of shrinkage and dissolved gas in the formation of microporosity.

Hydrogen may be intentionally added to counteract the more harmful effects of shrinkage on casting acceptability. For parts requiring only cosmetic as-cast appearance, there would appear to be no compelling reason not to add hydrogen by any number of means to improve superficial quality. However, for parts requiring structural integrity, machining, leak resistance, or other specific mechanical or physical characteristic, the intentional addition of hydrogen is unacceptable.

The precipitation of hydrogen during solidification offsets the negative relative pressures that develop when shrinkage voids form. The equalization of internal and external pressures brought about by hydrogen precipitation into internal shrinkage voids minimizes the tendency for surface collapse and wormhole shrinkage in the examples used earlier and alters the size and distribution of voids in a manner generally benefiting external appearance at the expense of internal quality and integrity.

The formation of hydrogen voids and the effects of hydrogen on internal shrinkage are influenced by entrained inclusions that nucleate precipitation. Because inclusions strongly facilitate bubble formation even at very low levels of dissolved hydrogen, it is important to consider the interaction rather than to attempt to correlate absolute hydrogen content with defect formation.

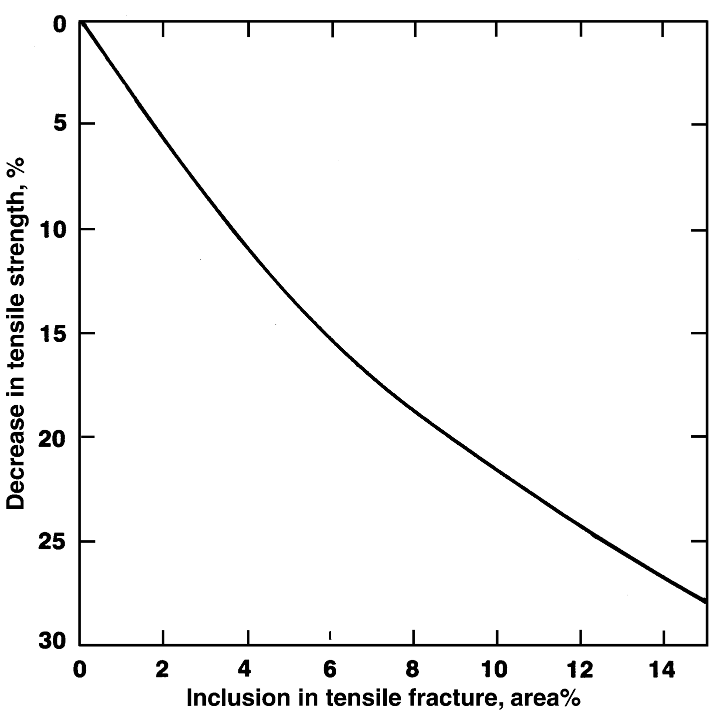

Fig. 5.7 Effect of inclusions on tensile strength of Al-12Si sand cast test bars. Inclusions decrease the tensile strength about twice as much as would be predicted on the basis of the decrease in cross section. Tensile strength at 0% inclusions = 27 ksi (186 MPa).

Layered feeding in castings can be exploited to improve casting results. The first metal that establishes stable contact with the mold wall begins solidifying and is fed not by the risering system but by immediately adjacent molten metal layers. In sand castings (low gradient), the last liquid to freeze may not be localized along the centerline. When the gradient is low and the freezing range large, liquid-solid mushy zones may exist throughout the casting in various stages of solidification, and changes in fraction solid from surface to center may be small. Nevertheless, localized gradients and the availability of thermally differentiated liquid at or near the solidification interface during and after mold filling result in unexpected soundness in areas in which shrinkage voids might otherwise be expected to occur. This principal is routinely applied in the casting of wrought alloy ingot by continuous and discontinuous direct chill casting processes. In these processes, the solidifying interface is constantly fed by newly introduced thermally differentiated molten alloy, and a degree of heat-flow equilibrium is established to provide solidification conditions that ensure minimum solidification zone growth accompanied by unlimited liquid feed and an adequate thermal gradient for the promotion of structural soundness. These principles are reflected in gating designs that approximate layering effects without resorting to more costly methods of promoting internal quality.

Finite-element modeling aimed at predicting mold and metal temperature distributions during and after mold filling, solidification patterns, and the required position, size, and configuration of risers has achieved valuable progress.

Porosity in castings, whether hydrogen voids, shrinkage, or the more usual defects that can be associated with both conditions, can be understood and prevented by:

- Melt treatment must be performed for effective removal of oxides and other entrained nonmetallics and the reduction in dissolved hydrogen concentration.
- Metal handling, pouring, and the design of the gating system must preserve minimum required molten metal quality.
- The gating and risering system with variable heat extraction techniques and application of the principles of directional solidification must be capable of minimizing or preventing shrinkage porosity.

It is important that void appearance and distribution be considered in defining the nature of porosity defects. The interactive effects of hydrogen, inclusions, and shrinkage should be considered in the development of appropriate corrective actions when unacceptable levels of porosity are experienced. Typically, hydrogen porosity appears as evenly distributed voids while shrinkage is more localized or concentrated. The distinctions are facilitated through radiographic analysis.

The presence of internal voids diminishes property capability (Fig. 5.8). The void fraction reduces the effective cross-sectional area under stress and void topography concentrates applied stresses to substantially lower tensile and yield strengths and elongation. The effect of void content on the tensile strengths of selected alloys is shown in Fig. 5.9.

5.5 Radiographic Inspection

Radiography and fluoroscopy are extensively used by the aluminum foundry industry to reveal internal discontinuities. Other means of assessing internal quality such as sectioning castings, metallography, and microradiography are destructive and offer only plane surfaces for examination. Radiographic methods permit nondestructive whole casting evaluation and the discrimination of shrinkage, hydrogen porosity, and more and less dense inclusions within limits of resolution.

X-ray testing is performed as a process-control tool and as a compliance test of casting acceptability. Ultrasonic and other acoustic techniques have not been proven for engineered aluminum castings.

Radiography is used to:

- Facilitate the optimization of gating design, processes, and practices in pilot stages through rapid comprehensive correlations with casting quality
- Inspect castings during production, as specified by the customer or foundry quality-control standards
- Confirm that specified internal quality standards have been met
- Inspect weldments and weld repairs

ASTM E 155, "Reference Radiographs for the Examination of Aluminum and Magnesium Castings," is the recommended refer-

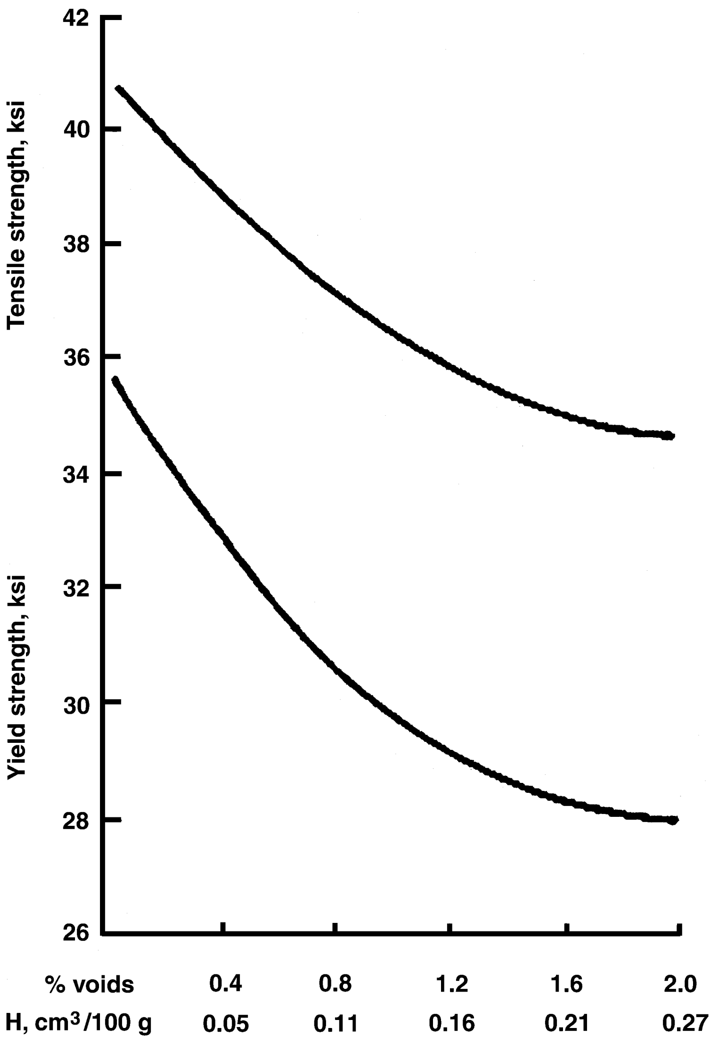

Fig. 5.8 Effect of hydrogen porosity on the tensile and yield strengths of alloy 356.0-T6 sand castings

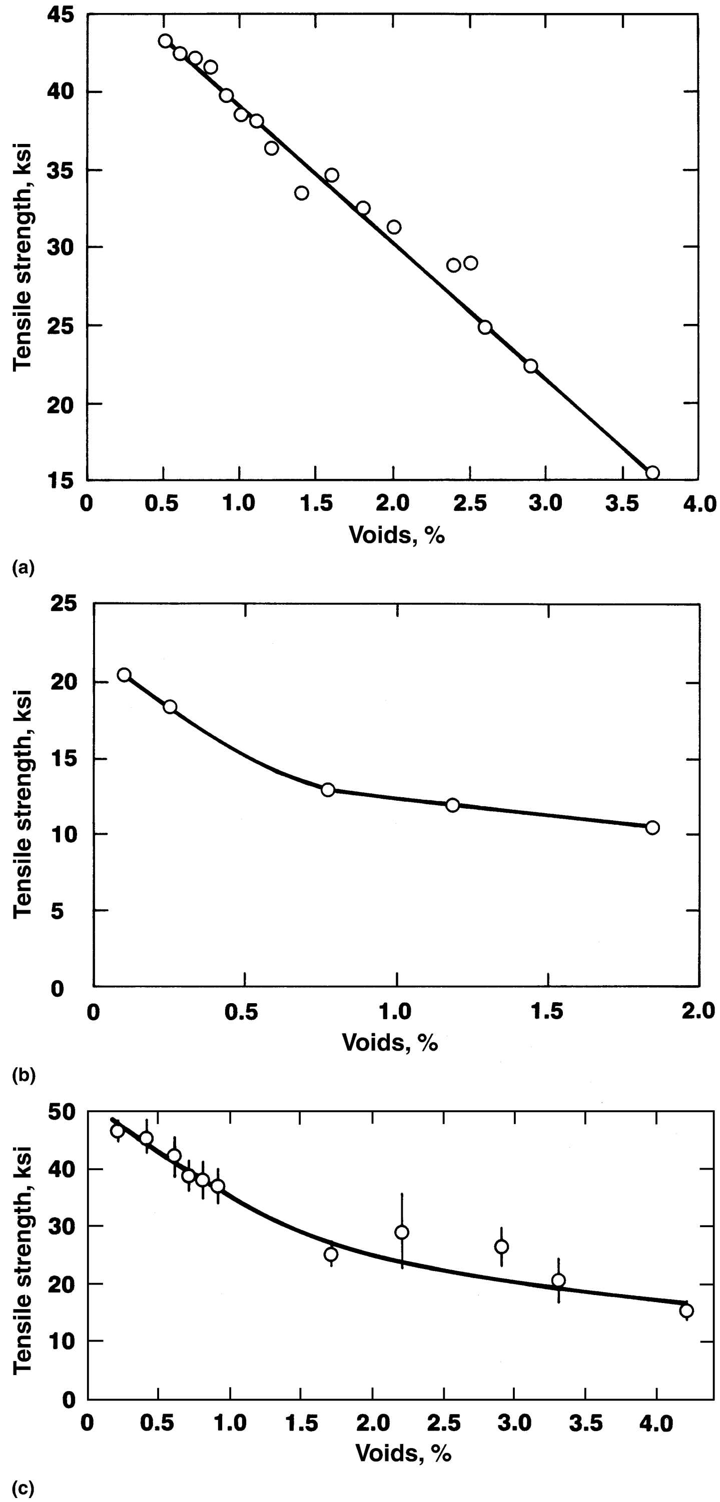

Fig. 5.9 Effect of void content on the tensile strengths of selected aluminum casting alloys. Large decreases in tensile strength are associated with relatively small increases in the amount of voids. (a) Alloy 355.0-T61. (b) Alloy 443.0-F. (c) Alloy 520.0-T4

ence for the interpretation of discontinuities as revealed by radiographic inspection. This ASTM standard and the Aluminum Association standards for aluminum sand and permanent mold casting are the recommended references for those needing more detailed information on radiographic inspection.

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CHAPTER 6

Hot Isostatic Processing

One very significant process refinement available to deal with internal porosity is hot isostatic pressing, commonly referred to as HIP or HIPping. This process deserves special attention for applications requiring very high quality and performance.

6.1 The HIP Process

Hot isostatic processing of castings is recognized as a means of providing improved internal soundness or integrity, increased density, and improved properties. The HIP process is applicable to a wide range of products in which these benefits justify its cost (Fig. 6.1). The process was developed to significantly improve the mechanical properties and fatigue strength of aluminum alloy sand and permanent mold castings. It has proved capable of substantially eliminating microporosity resulting from the precipitation of hydrogen and the formation of internal shrinkage during solidification. The process has no effect on cracks, shrinkage, and other defects that communicate to the casting surface.

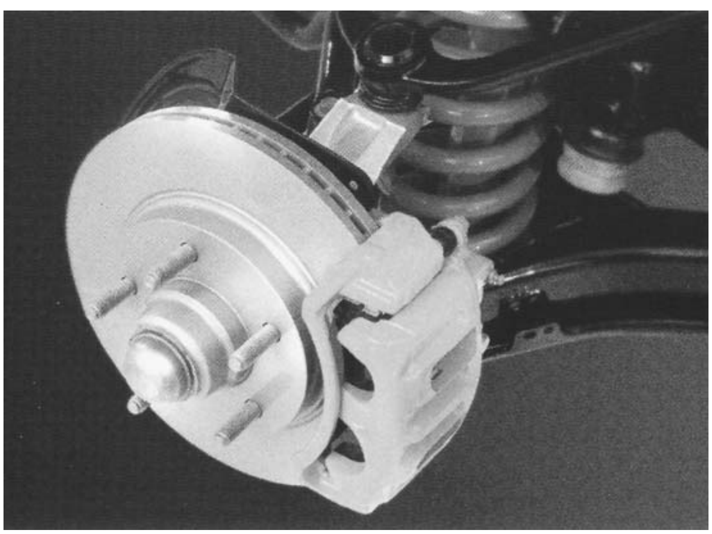

Fig. 6.1 Hot isostatically pressed cast aluminum brake caliper. Development of lower-cost HIP process alternatives since the 1990s is expanding its potential use into a broad range of applications, including aluminum automotive castings such as steering knuckles, brake calipers (pictured), and control arms. Source: Ref 1

The method makes possible the salvage of castings that have been rejected for reasons of internal porosity. This advantage is of more significant importance in the manufacture of castings subject to radiographic inspection when required levels of soundness are not achieved in the casting process. Furthermore, alloys not of a castability consistent with normal foundry requirements, but offering the potential for improved properties, may be cast in such a manner that application of the densification process would result in parts of acceptable quality and superior performance.

The principles of HIP are:

- At elevated temperatures and under increased pressure, limited but significant dissolution of hydrogen in the aluminum alloy matrix occurs, permitting the collapse and healing of void surfaces formed by hydrogen precipitation during solidification.
- At elevated temperatures and under increased pressure, precipitated hydrogen in excess of the solubility limit is compressed and repartitioned, or redistributed, resulting in increased structural density and integrity.
- At elevated temperatures and under increased pressure, shrinkage voids uncontaminated by hydrogen are compressed and healed by the collapse of the surrounding structures when yield strength is reduced sufficiently for plastic deformation to occur during the densification cycle.
- In the case of shrinkage voids contaminated by hydrogen, resolution of hydrogen and the collapse and metallurgical bonding of internal void surfaces occur by a combination of these effects.

Initial efforts to reduce porosity and increase density involved the application of pressure in metal dies. Mechanical densification as a concept for processing castings was abandoned as a result of a number of limitations. These included the cost of dies, processing costs equal to a forge finishing operation added to casting and processing costs, and the nonfeasibility of designing compression dies for complex casting configurations.

Hot isostatic pressure application was developed as a means of achieving both technical and economic objectives. Hot isostatic pressing takes place in an autoclave in which parts are exposed under pressure at elevated temperatures in a controlled atmosphere. Various production castings and powder metallurgical products are routinely HIPped in large commercial facilities.

6.2 The Effect of HIP on Tensile Properties

Densification (HIP) to various extents generally enhances tensile and yield strengths and improves ductility, most markedly in compositions more susceptible to internal porosity under normal casting conditions.

A comparison of tensile test results for cast plates with and without densification treatment is shown in Table 6.1; both the Alcoa A359 process (Ref 2) and the Densal II Process (Bodycote International) (Ref 3) are represented.

For the castings given the Alcoa A359 treatment, the internal quality of 332.0, A356.0, and A357.0 permanent mold castings had been intentionally degraded by a high level of hydrogen in the melt before the A359 process was applied. The Densal II treatment was applied to a commercially produced A356.0-T62 vacuum riserless casting/pressure riserless casting (VRC/PRC).

The data show that tensile and yield strength were improved by densification in every case of the degraded castings, and elongation was improved in most cases. For the Densal-treated castings, strength was not consistently affected significantly, but elongation was greatly enhanced.

Some of the Alcoa test plates given the hydrogen-degrading treatment beforehand exhibited progressively decreasing tensile properties from the bottom to the top of the casting; the data in Table 6.1 are presented in sequence of position in the castings and reflect this gradation. The A359 process treatment of these plates resulted in much more uniform properties.

Large numbers of additional tests by Alcoa, Bodycote, and others, and involving experimental and production castings have now been performed to confirm that HIP generally increases tensile and yield strengths and elongation. Experience also confirms that the treatment provides greater uniformity of tensile properties within most parts.

6.3 The Effect of HIP on Fatigue Performance

It was the significant positive effect of mechanical densification on fatigue properties that encouraged the commercial development of the HIP processes, and that beneficial effect is well illustrated by data for both the A359 and Densal II processes.

Table 6.2 summarizes the results of fatigue tests of six castings representing four different alloys given the Alcoa A359 process; all tests were run at 20 ksi (138 MPa). The Alcoa A359 HIP treatment resulted in an average increase of about 200%, with the range being 35 to 360%.

Complete fatigue curves were developed for only one alloy, 332.0-F, and that is shown in Fig. 6.2. The advantage for HIPped casting is apparent at all stress levels, and the endurance limit for the HIPped casting is almost 20% above that of the untreated casting.

From Table 6.2, it is clear that in cases where tests were run of untreated and treated samples at the same stress level of 20 ksi (140 MPa), the Alcoa A359 HIP treatment resulted in an average increase of about 200%. For 332.0-F, where the entire fatigue curve was determined (Fig. 6.2), the advantage for HIPped material was apparent at all stress levels, and the endurance limit for the HIPped material was almost 20% above that of the untreated casting.

Table 6.3 and Fig. 6.3 through 6.5 illustrate the effect of the Densal II HIP process on fatigue life.

The data in Table 6.3 illustrate that fatigue life was improved for D357.0-T6 castings with both acceptable and unacceptable levels of porosity based on radiographic examination, and that the effect was significantly greater for the casting with the greater porosity as indicated by the x-rays.

In a Weibull analysis for an A356.0-T6 casting (Fig. 6.3), Boileau, Zindel, and Allison (Ref 6) show a rather consistent order of magnitude increase in fatigue life for the HIPped sample. As illustrated in Fig. 6.4, such consistent increases were not found for VRC/PRC and sand castings, and in fact only small increases favoring the HIPped samples are apparent; perhaps this reflects the higher quality of the VRC/PRC casting in the first place. Data from Bodycote (Fig. 6.5) seem to support the significant advantage of their Densal process at all stress levels for 359.0-T6, with an apparent improvement in endurance limit of almost 50%.

Based on the data available, it is reasonable to anticipate that HIP will likely improve fatigue properties, and that the magnitude of the improvement may be greatest in cases where significant porosity is present, especially near the surfaces.

6.4 Radiographic Inspection of HIPped Castings

Radiographs of laboratory-prepared permanent mold cast plates indicated that most but not all porosity was eliminated or reduced beyond x-ray resolution (Fig. 6.6 and 6.7). Voids that communicated to the surface including shrinkage porosity extending into the casting from the riser were not affected. Some voids in close proximity to the surface, but lacking communication, collapsed, resulting in indentations.

Comparison radiographs of whole production castings also reflected the dramatic improvement in radiographic quality through HIP. In many instances, improvements in radiographic quality were consistent with the most challenging specification requirements.

The HIP cycle could be used in solution heat treatment. Processing costs and the incompatibility of cycles in which solution heat treatment requires up to six times that required for densification makes that impractical, but parts could be partially solution heat treated and then transferred at temperature to the autoclave for completion of HIP and solution treatments.

Casting methods can be used to minimize the presence of undensifiable porosity on casting surfaces, leading to the wider applicability of HIP to cast parts. Surface treatments may also be used to enhance the densification of surface related porosity.

Process success is a consequence of the combined effect of external pressure and temperature that causes the collapse of internal voids through plastic deformation. Hydrogen solubility is directly related to the square root of the pressure and calculations indicate that at 930 °F (500 °C), hydrogen solubility increases 32 times at an external pressure of 15 ksi (105 MPa). Since the solubility of hydrogen in aluminum at 930 °F (500 °C) is approximately 0.003 mL per 100 g, the amount of hydrogen that can be dissolved through HIP treatment approximates 0.10 mL per 100 g. At reasonable hydrogen levels, void compression and the redistribution or repartition of precipitated hydrogen through HIP results in essentially closed porosity. Extensive reheat treatment at ambient

Table 6.1 Effect of HIP on tensile properties of representative aluminum alloy castings

Values are averages for an unspecified number of tests of specimens from castings.

			Untreated					HIPped						Improvement HIPped/unHIPped, %			
			Ultimate strength		Yield strength(a)		Elongation (2*D* or 4*D*), %		Ultimate strength		Yield strength(a)		Elongation (2*D* or 4*D*), %			Elon-	
Alloy	**Temper**	**Casting process**	**ksi**	**MPa**	**ksi**	**MPa**		**HIP process**	**ksi**	**MPa**	**ksi**	**MPa**		**UTS**	**TYS(a)**	**gation**	**Ref**
332.0	T6	Permanent mold	33.0	228	31.1	214	0.5	A359	38.8	268	34.0	234	0.5				2
			28.1	194	...	...	0.5	A359	35.6	246	34.1	235	0.5				
			27.0	186	...	...	0.5	A359	35.5	245	33.6	232	0.5				
		Average	**29.4**	**202.5**	**31.1**	**214.0**	**0.5**		**36.6**	**253**	**33.9**	**234**	**0.5**	**25**	**9**	**0**	
	T6	Typical, permanent mold	36	248	28	193	17.0										
A356.0	T6	Sand	37.6	259	34.4	237	2.0	Densal II	36.5	252	33.1	228	2.0				4
			38.1	263	35.2	243	5.3		36.4	251	35.4	244	5.9				
		Average	**37.8**	**261**	**34.8**	**240**	**3.7**		**36.5**	**252**	**34.2**	**236**	**3.9**	**–3**	**–2**	**5**	
A356.0	T61	Permanent mold	35.6	246	27.1	187	4.5	A359	38.8	268	30.8	212	4.5				2
			34.8	240	27.3	188	4.0	A359	37.4	258	30.7	212	3.5				
			34.0	234	27.4	189	4.0	A359	36.7	253	30.3	209	3.0				
			33.2	229	27.3	188	2.5	A359	36.9	254	30.1	208	3.0				
			30.2	208	25.7	177	2.0	A359	36.4	251	29.3	202	3.5				
			39.8	275	29.4	203	6.5	A359	42.7	295	31.6	218	10.0				
			37.9	261	30.3	209	4.5	A359	42.4	292	32.6	225	6.5				
			36.5	252	29.2	201	2.5	A359	41.6	287	31.3	216	6.5				
			35.5	245	28.5	197	2.5	A359	41.6	287	31.6	218	6.0				
			33.6	232	27.8	192	3.0	A359	41.2	284	32.7	226	6.0				
		Average	**35.1**	**242**	**28**	**193**	**4**		**39.6**	**273**	**31.1**	**214**	**5**	**13**	**11**	**46**	
	T61	Typical, permanent mold	41	283	30	207	10.0										
A356.0	T62	VRC/PRC	44.5	307	34.5	238	9.0	Densal II	43.8	302	32.8	226	10.4	–2	–5	16	3
	T62	Typical, permanent mold															
A357.0	T62	Permanent mold	43.6	301	38.9	268	1.0	A359	47.7	329	40.8	281	3.0				2
			41.1	283	38.3	264	0.5	A359	47.2	326	42.1	290	2.5				
			35.5	245	...	...	0.5	A359	46.7	322	41.1	283	2.0				
		Average	**40.1**	**276**	**38.6**	**266**	**0.7**		**47.2**	**326**	**41.3**	**285**	**3**	**18**	**7**	**275**	
	T62	Typical, permanent mold	62	428	38	262	17.0										
D357.0	T6	Investment (Acceptable x-rays)	51.8	357	39.1	270	7.9	Densal II	50.2	346	39.1	270	4.2				4
			50.7	350	36.2	250	6.7		50.2	346	38.0	262	6.7				
			50.9	351	39.7	274	4.2		51.8	357	39.7	274	7.4				
			50.2	346	38.9	268	5.1										
		Average	**50.9**	**351**	**38.6**	**266**	**6.0**		**50.7**	**350**	**39.0**	**269**	**6.1**	**–0**	**1**	**2**	
D357.0	T6	Investment (unacceptable x-rays)	43.1	297	37.8	261	1.2	Densal II	50.5	348	37.4	258	4.9				4
			44.9	310	36.2	250	2.1		50.9	351	41.5	286	4.0				
			41.5	286	35.2	243	1.5		50.3	347	39.7	274	3.5				
			...	...	...	...	...		50.5	348	39.4	272	3.8				
			...	...	...	...	...		52.1	359	41.9	289	5.4				
			...	...	...	...	...		49.7	343	40.7	281	3.5				
			...	...	...	...	...		49.2	339	25.2	174	3.5				
		Average	**43.2**	**298**	**36.4**	**251**	**1.6**		**50.5**	**348**	**40.0**	**276**	**4.1**	**17**	**10**	**148**	
Average improvement by HIPing														10%	5%	70%	

(a) For tensile yield strengths, offset = 0.2%. Source: Ref 2–4

Table 6.2 Effect of HIP by Alcoa Process on fatigue life of representative aluminum alloy castings

Hot isostatic pressing (HIP) by Alcoa 359 process

Alloy	Temper	Type of casting(a)	Lot ID	Fatigue stress, ksi Smooth ksi	Fatigue stress, ksi Smooth MPa	Fatigue life Untreated cycles	Fatigue life HIPped(b) cycles	Improvement HIPped/UnHIPped(b)
242.0	F	PM pistons	317843,4	20.0	138	0.6×10^6	1.55×10^6	
						1.0×10^6	1.75×10^6	
						1.45×10^6	1.9×10^6	
						2.35×10^6	2.1×10^6	
					Average	$\mathbf{1.35 \times 10^6}$	$\mathbf{1.82 \times 10^6}$	**35%**
332.0	F	PM casting	317439,437	20.0	138	6×10^4	2.05×10^5	
				20.0	138	...	1.6×10^5	
					Average	$\mathbf{6 \times 10^4}$	$\mathbf{1.82 \times 10^5}$	**203%**
354.0	T61	Sand cast part	317433,2	20.0	138	2.1×10^5	7.6×10^5	
						1.6×10^5	7.1×10^5	
						0.94×10^5	6.2×10^5	
						...	4.8×10^5	
					Average	$\mathbf{1.55 \times 10^5}$	$\mathbf{6.39 \times 10^5}$	**312%**
354.0	T61	PM cast part	317429,428	20.0	138	7.2×10^5	3.05×10^6	
						6.3×10^5	2.8×10^6	
						4.5×10^5	2.3×10^6	
						2.1×10^5	1.5×10^6	
					Average	$\mathbf{5.24 \times 10^5}$	$\mathbf{2.41 \times 10^6}$	**360%**
A356.0	T61	Sand cast part	317435,434	20.0	138	1.35×10^5	4.3×10^5	
						0.97×10^5	3.1×10^5	
						0.92×10^5	2.05×10^5	
						0.85×10^5	1.6×10^5	
					Average	$\mathbf{1.02 \times 10^5}$	$\mathbf{2.79 \times 10^5}$	**174%**
A356.0	T61	PM cast part	317431,430	20.0	138	1.95×10^5	4.4×10^5	
						1.4×10^5	3.3×10^5	
						1.3×10^5	2.9×10^5	
						1.15×10^5	2.1×10^5	
					Average	$\mathbf{1.45 \times 10^5}$	$\mathbf{3.33 \times 10^5}$	**130%**
				Average increase in fatigue life at 20 ksi (138 MPa)				**202%**

(a) Casting process and part shape if known; PM, permanent mold. (b) Percent improvement by HIP in fatigue strength or endurance limit as compared to unHIPped material from same lot. Source: Ref 5

pressure can, in the worst cases, result in the reformation of internal porosity. In the case of castings with high hydrogen contents, this effect is seen following the heat treatment of HIPped parts.

The extent of outgassing occurring through diffusion in the HIP treatment cycle is insignificant.

Hot isostatic pressing is capable of upgrading mechanical properties and internal soundness and dramatically improving fatigue performance in a wide range of sand and permanent mold cast parts. The process can result in the salvage of unsatisfactory quality castings, an upgrading of mechanical properties for purposes of specification compliance, and substantial improvement in radiographic inspection capability.

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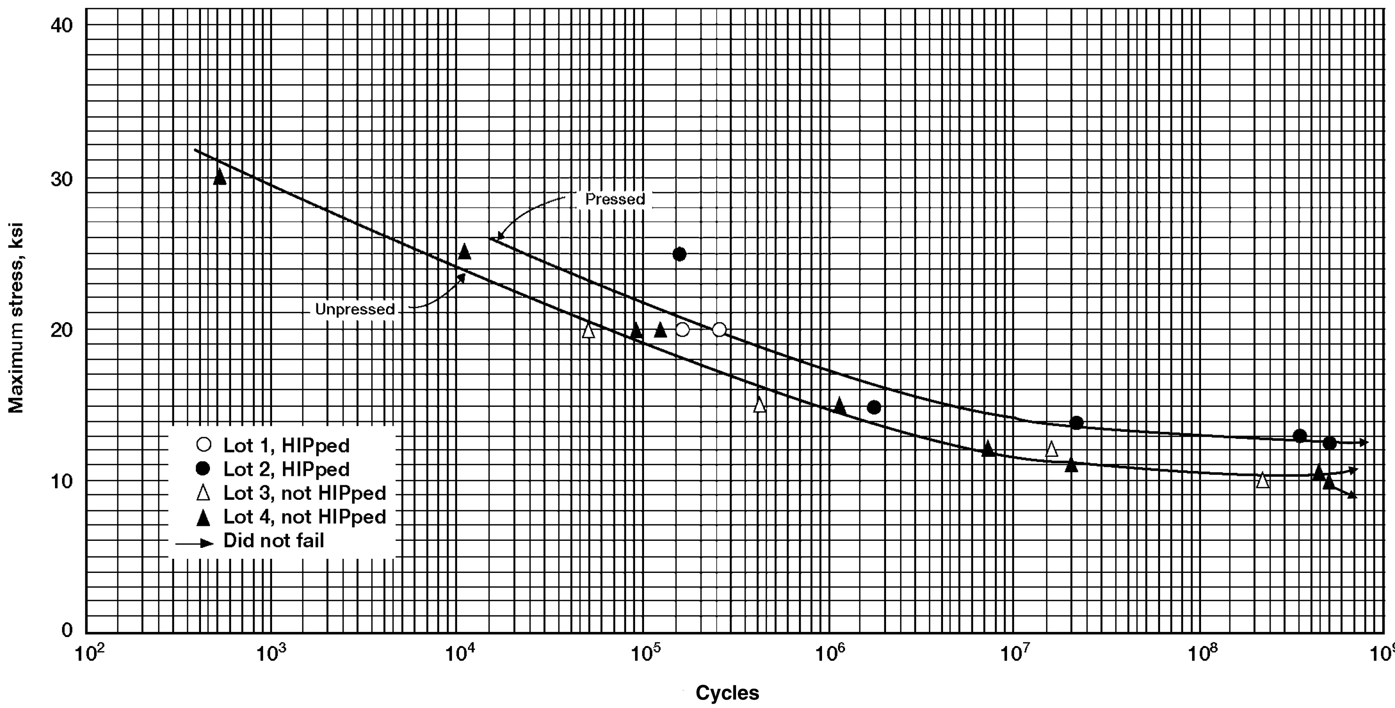

Fig. 6.2 Effect of Alcoa A359 HIP process on the rotating beam fatigue life of a 332.0-F casting (specimen per Fig. A3.2 in Appendix 3)

Table 6.3 Effect of HIP by Densal II on fatigue life of representative aluminum alloy castings

Alloy	Temper	Type of casting	Fatigue stress, smooth ksi	Fatigue stress, smooth MPa	Fatigue life Untreated cycles	Fatigue life HIPped cycles	Improvement(a)
D357.0	T6	Investment (acceptable x-rays)	26.4	182	19,337	177,169	
					63,515	174,555	
					69,824	161,533	
					94,191	130,645	
					60,986	84,000	
					80,524	199,535	
					39,271	121,004	
					31,126	164,405	
					34,240	125,950	
					29,200	144,569	
					...	163,364	
				Average	**52,221**	**149,703**	**187%**
D357.0	T6	Investment (unacceptable x-rays)	26.4	182	15,509	136,361	
					19,718	133,401	
					16,501	49,067	
					13,447	63,190	
					13,795	130,114	
					5,121	143,122	
					19,210	142,519	
					10,147	154,453	
					10,763	160,191	
					2,444	178,372	
					60,707	63,357	
					...	146,253	
					...	152,991	
					...	172,748	
					...	119,570	
					...	69,473	
					...	22,604	
					...	125,499	
				Average	**17,033**	**120,183**	**606%**

(a) Percent improvement by HIP in fatigue strength or endurance limit as compared to unHIPped material from same lot. Source: Ref 4

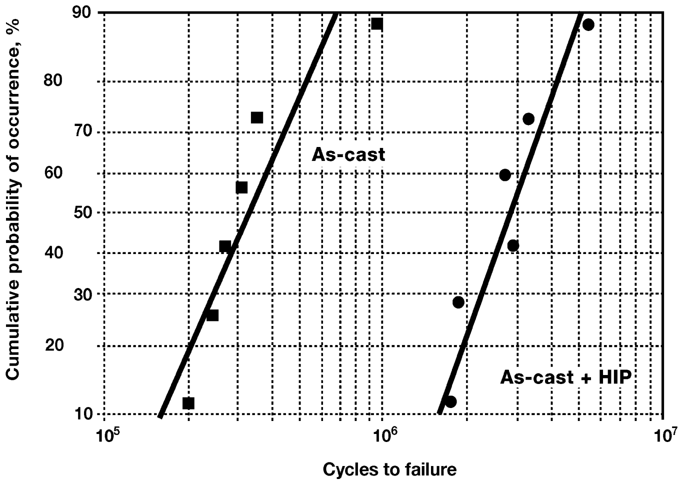

Fig. 6.3 Weibull analysis of fatigue data for A357.0-T6 aluminum alloy castings with and without Densal II HIP. Source: Ref 6

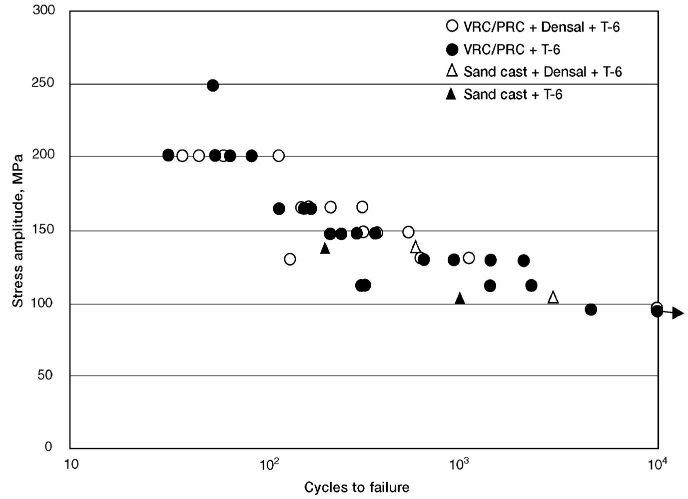

Fig. 6.4 Fatigue *S-N* curves for VCR/PCR and sand cast A356.0-T6 aluminum alloy castings with and without Densal II HIP

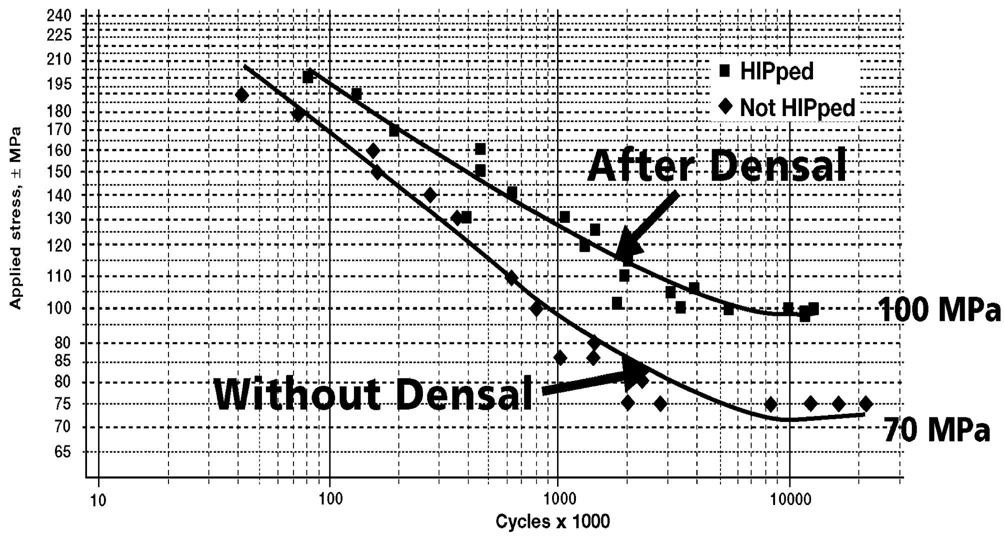

Fig. 6.5 Rotating bending fatigue *S-N* curves ($R = -1.0$) for gravity die cast 359.0-T64 aluminum alloy casting with and without Densal II HIP

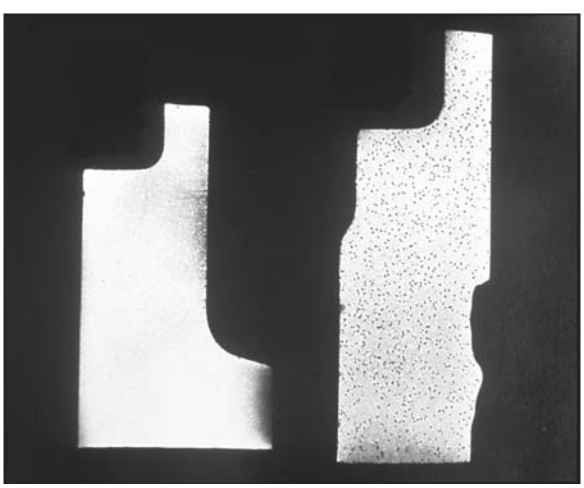

Fig. 6.6 Radiographs showing an untreated A356 alloy cast section with heavy porosity (right) and after hot isostatic pressing (left)

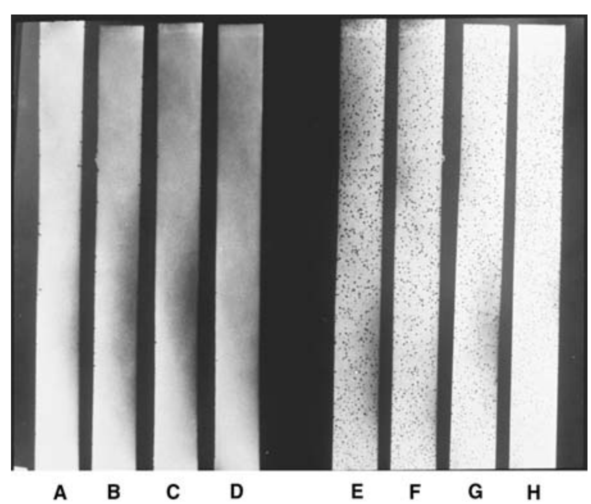

Fig. 6.7 Thin-section radiographs taken from A356 plate casting sections at one-inch intervals: A–D after HIP treatment, E–H as cast

Aluminum Alloy Castings: Properties, Processes, and Applications
J.G. Kaufman, E.L. Rooy, p 61-68
DOI:10.1361/aacp2004p061

CHAPTER 7

Heat Treatment of Aluminum Castings

The metallurgy of aluminum and its alloys offers a range of opportunities for employing thermal treatment practices to obtain desirable combinations of mechanical and physical properties. Through temper selection, it is possible to achieve properties that are largely responsible for the current use of aluminum alloy castings in virtually every field of application.

The term heat treatment is used to describe all thermal practices intended to modify the metallurgical structure of products in such a way that physical and mechanical characteristics are controllably altered to meet specific engineering criteria.

One or more of the following objectives form the basis for temper selection:

- Increase hardness
- Improve machinability
- Improve wear resistance
- Increase strength and/or produce the mechanical properties specified for a particular material condition
- Stabilize mechanical and physical properties
- Ensure dimensional stability
- Alter electrical characteristics
- Alter corrosion resistance
- Relieve residual stresses

The versatility of aluminum is reflected by the number of alloys that have been developed and commercially used. A wide range in desirable combinations of mechanical and physical properties can be achieved through the heat treatment of many of these alloys.

To achieve any of these objectives, parts may be annealed, solution heat treated, quenched, precipitation hardened, overaged, or treated in combinations of these practices (Fig. 7.1). In some simple shapes, bearings for example, thermal treatment may also include postquench plastic deformation through compression.

As noted in Chapter 2, the Aluminum Association has standardized the definitions and nomenclature applicable to thermal prac-

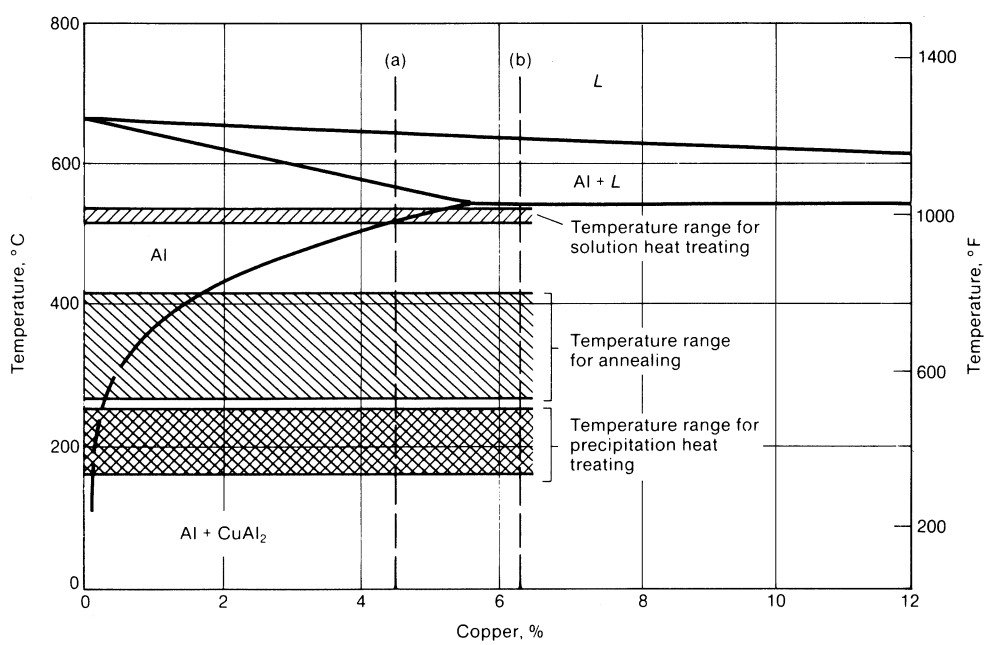

Fig. 7.1 Typical temperature ranges for various thermal operations for aluminum alloy castings superimposed on a binary aluminum-copper phase diagram. The vertical dashed lines represent alloys containing (a) 4.5% Cu and (b) 6.3% Cu.

tice types and maintains a registry of standard heat treatment practices and designations for industry use:

- F, as-cast
- O, annealed
- T2, annealed (obsolete designation; use O instead)
- T4, solution heat treated and quenched
- T5, artificially aged from the as-cast condition
- T6, solution heat treated, quenched, and artificially aged
- T7, solution heat treated, quenched, and overaged

For tempers T4 through T7, additional digits such as T5x, T5xx, T6x, etc. may be used to define practice variations. The T101 temper has been assigned to a compressively cold-worked condition applicable only to alloy x850.0.

Specific criteria for heat treatment and the practices that will be used are often separately negotiated between buyer and seller.

The heat treatment of aluminum alloys is based on the varying solubilities of metallurgical phases in a crystallographically monotropic system. Since solubility of the eutectic phase increases with increasing temperature to the solidus, the formation and distribution of precipitated phases can be manipulated to influence material properties.

In addition to phase and morphology changes associated with soluble elements and compounds, other (sometimes desirable) effects accompany elevated-temperature treatment. Microsegregation in all solidified structures is minimized or eliminated. Residual stresses caused by solidification or by prior quenching are reduced, insoluble phases may be physically altered, and susceptibility to corrosion may be affected.

7.1 Solution Heat Treatment

Exposure to temperatures corresponding to maximum safe limits relative to the lowest melting temperature for a specific heat treatable composition results in dissolution of soluble phases that formed during and after solidification. The rate of heating to solution temperature is technically unimportant. When more than one soluble phase is present such as in Al-Si-Cu-Mg and Al-Zn-Cu-Mg systems, stepped heat treatment may be required to avoid melting of lower-melting-temperature phases.

The most complete degree of solution that can be practically and economically achieved is desirable for optimal properties. Different casting processes and foundry practices result in microstructural differences with relevance to heat treatment practice. Coarser microstructures associated with slow-solidification-rate processes require longer exposure at solution heat treatment temperature for solution to be achieved. The time required at temperature is typically progressively shorter for investment, sand, and permanent mold castings, but thin-walled sand castings produced with extensive use of chills can also often display finer microstructures. For these reasons, solution heat treatment practices may be optimized for any specific part to achieve solution with the shortest reasonable cycle once a production practice is finalized. Most foundries and heat treaters will select a solution heat treatment practice with a large margin of safety to avoid the delays and costs of reheat treatment when property limits are not met.

Because of the changing slope of the characteristic solvus as temperature approaches the eutectic melting point, solution heat treatment temperature is critical in determining the degree of solution that can be attained. There is, furthermore, the effect of temperature on diffusion rates, which directly influences degree of solution as a function of time at temperature.

Within temperature ranges defined for solution heat treatment by applicable specification lies a significant corresponding range of solution potentials. The knowledgeable heat treatment facility or foundry seeking to obtain superior properties will bias solution heat treatment temperature within specification limits to obtain the highest practical degree of solution. Superior properties can be achieved with furnaces, thermocouples, and furnace controls that are capable of operating within close temperature ranges near the eutectic melting region, recognizing the resistance of cast structures to melting based on diffusion considerations. While temperatures just below the eutectic melting point are desirable for optimal property development, it is critically important that eutectic melting resulting in brittle intergranular eutectic networks be avoided.

Insoluble phases including those containing impurity elements are normally thought to be unaffected by solution heat treatment. However, limited changes do occur. The surfaces of primary and eutectic silicon particles are characteristically rounded during solution heat treatment. The solution heat treatment of alloy A444.0, which contains no soluble phase, is justified solely by this phenomenon and its effect on ductility. Limited solubility also results in similar physical boundary changes in other insoluble intermetallics.

7.2 Quenching

The objective of quenching is retention of the highest possible degree of solution with the lowest level of induced residual stresses and the least warpage or distortion consistent with commercial or specified requirements. Quenching is a distinct step in thermal practice leading to the metastable, supersaturated solution heat treated condition, T4. Specific parameters may be associated with the heating of parts to achieve solution, and separate parameters apply to the steps required to achieve the highest postquench degree of retained solution. Rapid cooling from solution temperature to room temperature is critical, difficult, and often the least-controlled step in thermal processing.

Specifications often define or recommend quench delay limits. In practice, the shortest possible delay is desirable. Specialized equipment such as bottom-drop and continuous furnaces offer these advantages. Excessive delays result in temperature drop and the rapid formation of coarse precipitates in a temperature range at which the effects of precipitation are ineffective for hardening purposes. The slope of the temperature-time relationship during quenching from solution temperature should be sufficiently steep that limits of precipitate solubility are not intersected (Fig. 7.2). Even though castings are characteristically more tolerant of quench delay than wrought products because of coarser structures and

longer diffusion times, excessive quench delays nevertheless result in less-than-optimal strengthening potential.

Water is the quench medium of choice for aluminum alloys, and its temperature has a major effect on results. Most commercial quenching is accomplished in water entered near the boiling point, but room temperature, 150 °F (65 °C), and 180 °F (80 °C) are common standardized alternatives. Effects of thickness and quenchant temperature on average cooling rates at midplane are shown in Fig. 7.3. Figure 7.4 shows differences in mechanical properties that result from quenching in water at different temperatures.

Since higher potential strength is associated with the most rapid quenching and, in general, corrosion and stress-corrosion performance are enhanced by rapid quenching, it would appear that room-temperature water should routinely be employed. More severe quenching offers diminishing benefits in property potentials and significant increases in residual stresses and distortion. Quenchant temperature is the dominant factor in these considerations.

The key to the compromise between goals involving property development and the physical consequences of quenching is heat-extraction uniformity, which is in turn a complex function of the operable heat-extraction mechanism. Nucleant, vapor film, and convective boiling occur with dramatically different heat-extraction rates at different temperature intervals, section thickness, and surface conditions. Load density, positioning, and casting geometry influence the results. As section thicknesses increase, the metallurgical advantage of quench rates obtained by water temperatures less than 150 °F (65 °C) diminish, but the cooling rate advantage of 150 °F (65 °C) versus 212 °F (100 °C) water quench temperature is retained independent of section thickness.

In addition to developing racking and loading methods that space and orient parts for most uniform quenching, quenchant additions are often made to:

- Promote stable vapor film boiling by the deposition of compounds on the surface of parts as they are submerged in the quench solution
- Suppress variations in heat flux by increasing vapor film boiling stability through chemically decreased surface tension
- Moderate quench rate for a given water temperature

Quenching rates are also affected by surface condition of the parts. More rapid quenching occurs with oxidized, stained, and rough surfaces while bright, freshly machined, and etched surfaces quench more slowly.

The common use of water as a quenching medium is largely based on its superiority in heat extraction relative to other materials. Nevertheless, quenching has been accomplished in oil, salt baths, and in organic solutions. For many compositions, fan or mist

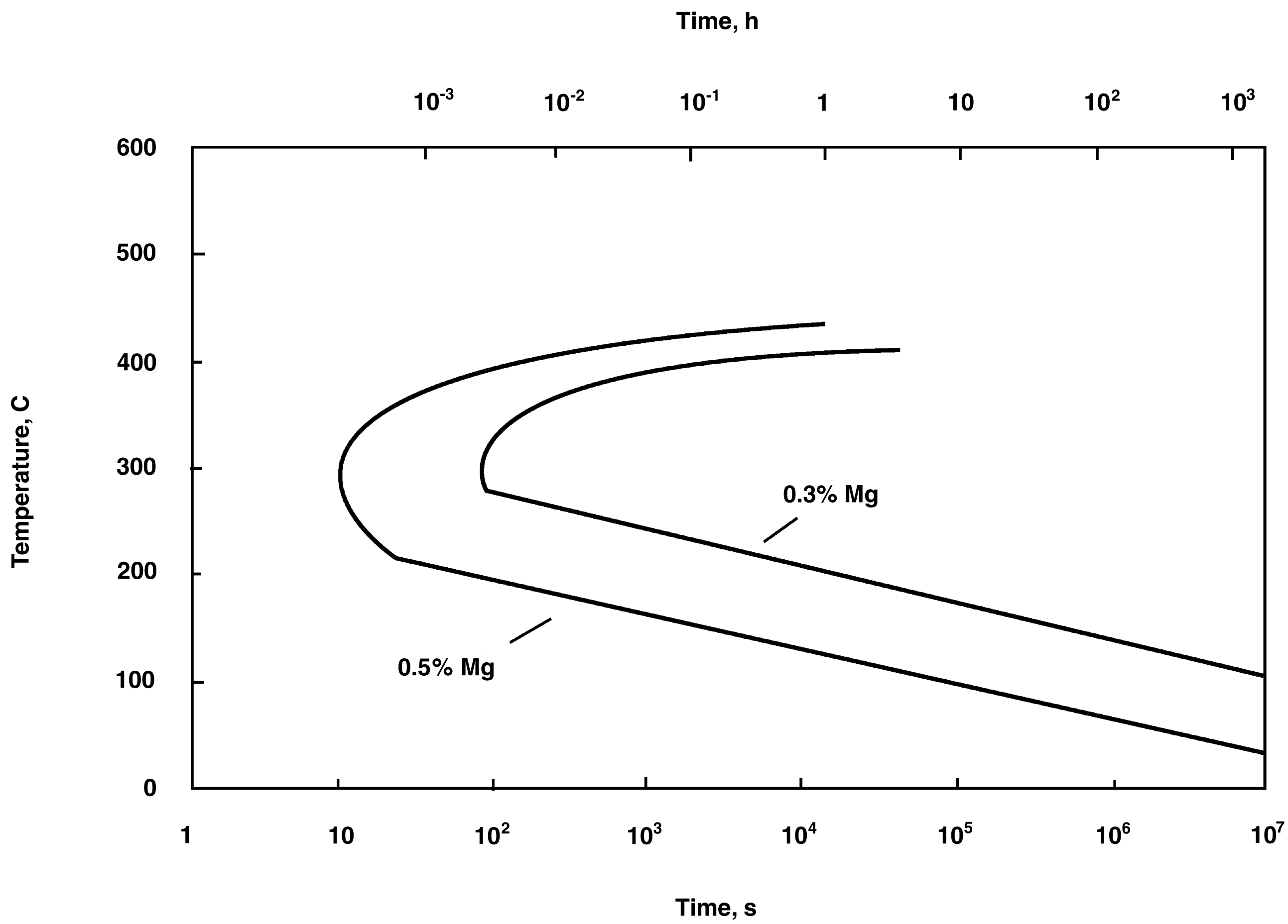

Fig. 7.2 Time-temperature-precipitation chart for aluminum alloys containing 7% Al and varying amounts of magnesium

quench is feasible as a means of obtaining dramatic reductions in residual stress levels at considerable sacrifice in hardening potential.

In general, parts that have been solution heat treated and quenched display tensile properties and elongation superior to those of the as-cast, F, condition. It is unique in improving strength, hardness, and ductility. Typical thermal treatments sacrifice strength and hardness for elongation or develop strength and hardness at the expense of ductility. The T4 condition is, however, rarely employed. Instead, the advantages of aging or precipitation hardening are obtained by additional thermal treatment following quenching. Among these advantages are increased strength and hardness with a corresponding sacrifice in ductility, improved machinability, the development of more stable mechanical properties, and reduced residual stresses.

7.3 Precipitation Heat Treating/Aging

Natural or artificial precipitation hardening following solution heat treatment and quench most powerfully differentiates the properties of cast aluminum products. Hardening is defined as changes in metallurgical structure resulting in increased resistance to deformation.

Most aluminum alloys age harden to some extent naturally after quenching; that is, properties change as a function of time at room temperature solely as a result of Guinier-Preston (GP) zone formation within the lattice structure. The extent of change is highly alloy dependent. For example, room-temperature aging in alloys such as A356.0 and C355.0 occurs within 48 h with insignificant changes thereafter. Alloy 520.0, normally used in the T4 condition, age hardens over a period of years, and a number of Al-Zn-Mg alloys that are employed without heat treatment exhibit rapid changes in properties over three or four weeks and harden at progressively reduced rates thereafter.

The process of hardening is accelerated by artificially aging at temperatures ranging from approximately 200 to 500 °F (90 to 260 °C), depending on the alloy and the properties desired. In natural and artificial aging, supersaturation, which characterizes the room-temperature solution condition, is relieved by the precipitation of solute that proceeds in stages with specific structural effects. At room or low aging temperatures or during transition at higher temperatures, the principal change is the diffusion of solute atoms to high-energy sites such as dislocations, dislocation tangles, and vacancies within the crystal lattice producing distortion of lattice planes and forming concentrations of subcritical crystal nuclei.

With continued exposure at aging temperature, these sites reach, or fail to reach, critical nucleation size, a stage leading to the

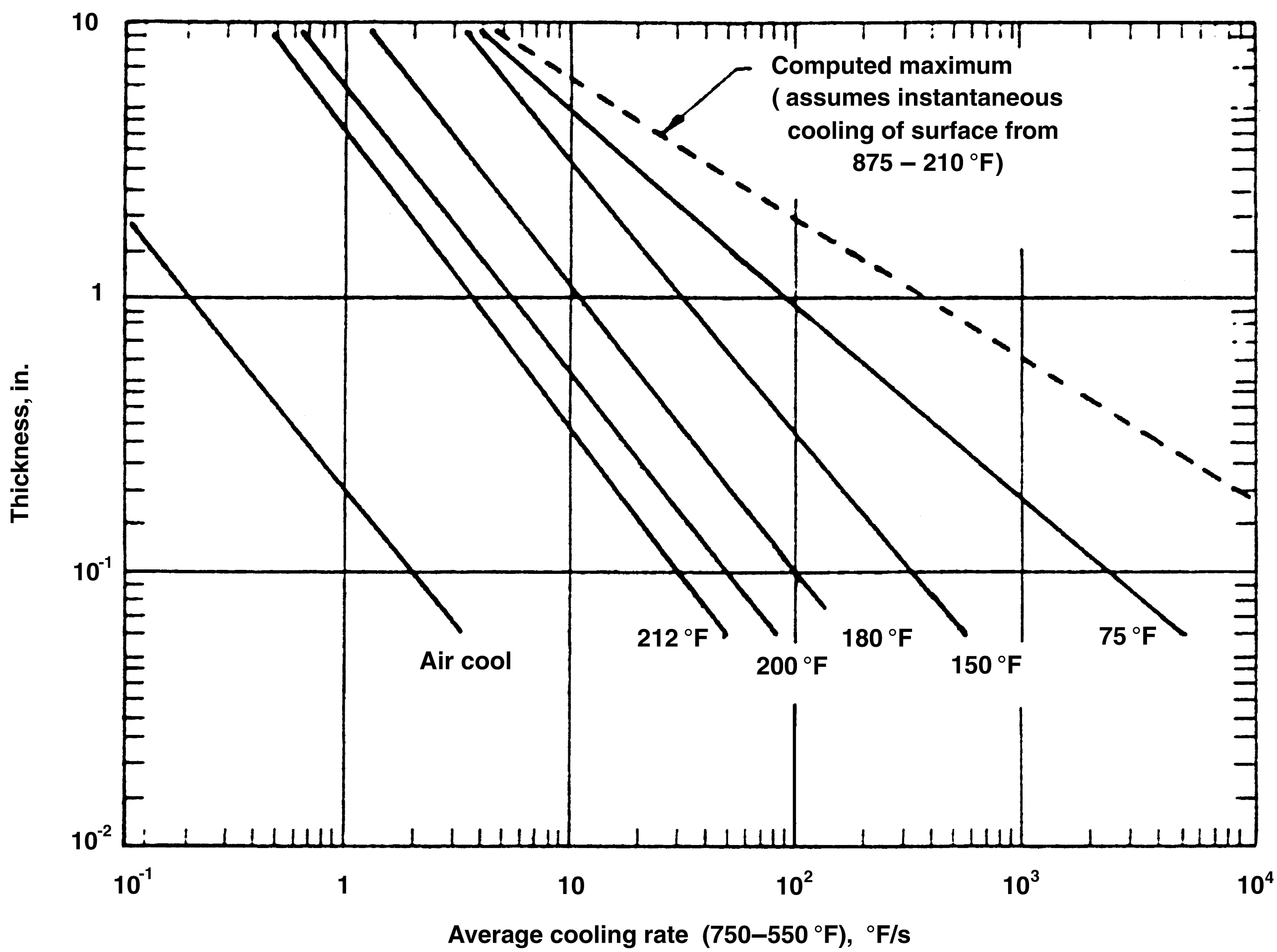

Fig. 7.3 Midplane cooling rates for varying water quench temperatures and aluminum alloy casting thicknesses

formation of discrete particles displaying the identifiable crystallographic character of the precipitated phase. With additional treatment, these transitional phase particles grow with an increase in coherency strains until with sufficient time and temperature, interfacial bond strength is exceeded. Coherency is lost, and with it, the strengthening effects associated with precipitate formation and growth. Continued growth of the now equilibrium phase occurs with the loss of hardness and strength corresponding to the overaged condition.

7.3.1 Aluminum-Copper

The soluble phase in aluminum-copper alloys is copper aluminide ($CuAl_2$). At temperatures above 212 °F (100 °C), GP zones that form by diffusion of copper atoms in the supersaturated solid solution (SS) are replaced by θ'', sometimes referred to as GP[2], with an ordered three-dimensional atomic arrangement. Continued diffusion and growth lead to the formation of the transition phase θ', which has the same composition and structure as the stable θ phase and maintains coherency with the crystal lattice. Finally, as discrete transition phase regions continue to grow, θ' transforms to stable, noncoherent equilibrium θ:

$$\theta = CuAl_2$$

$$SS \rightarrow GP \rightarrow \theta'' \rightarrow \theta' \rightarrow \theta$$

7.3.2 Aluminum-Copper-Magnesium

A similar sequence occurs in the artificial age hardening of Al-Cu-Mg alloys. The addition of magnesium accelerates and intensifies room-temperature aging, and the progression is from GP zones to the transition and stable equilibrium phases:

$$S = Al_2CuMg$$

$$SS \rightarrow GP \rightarrow S' \rightarrow S$$

7.3.3 Aluminum-Silicon-Magnesium

Magnesium silicide is the soluble phase in important alloys such as 356.0, A356.0, and A357.0 alloys. Unlike the hardening that accompanies the development of coherent lattice strains, this phase acts to increase the energy required for deformation of the crystal lattice. Spherical zones convert to needle-shaped particles at points corresponding to peak hardening. Further aging produces rod-shaped particles. The transition from β' to equilibrium Mg_2Si occurs without further diffusion:

$$\beta = Mg_2Si$$

$$SS \rightarrow GP \rightarrow \beta' \rightarrow \beta$$

7.3.4 Aluminum-Zinc-Magnesium

Several hardening phases may be formed in Al-Zn-Mg alloys. Most alloys of this type room-temperature age for extended periods. The presence of M and T in precipitation-hardened alloys such as 712.0, 713.0, and 771.0 is largely dictated by composition, but both may be present. M′ is less effective in strength development, and transition to the stable forms occurs rapidly at conventional aging temperatures:

$$M = MgZn_2$$

$$T = Mg_3Zn_3Al_2$$

$$\begin{array}{c} SS \rightarrow GP \rightarrow M' \rightarrow M \\ \downarrow \\ T' \rightarrow T \end{array}$$

The practice to be employed in artificial aging is entirely dependent on the desired level of property/strength development. Aging curves facilitate process selection. The heat treater may reasonably predict the results of aging by reference to these curves (see Data Set 1). It should be noted that longer times at lower aging temperature generally result in higher peak strengths. The aging response, or rate of property change as a function of time at peak strength, is also of interest. The flatter curves associated with lower aging temperatures allow greater tolerance in the effects of time/temperature variations.

Unlike solution heat treatment, the time required to reach aging temperature may be significant, but is seldom included in age-cycle control. The energy imparted during heating to precipitation-hardening temperature may be integrated into the control sequence to more accurately control results and minimize cycle time.

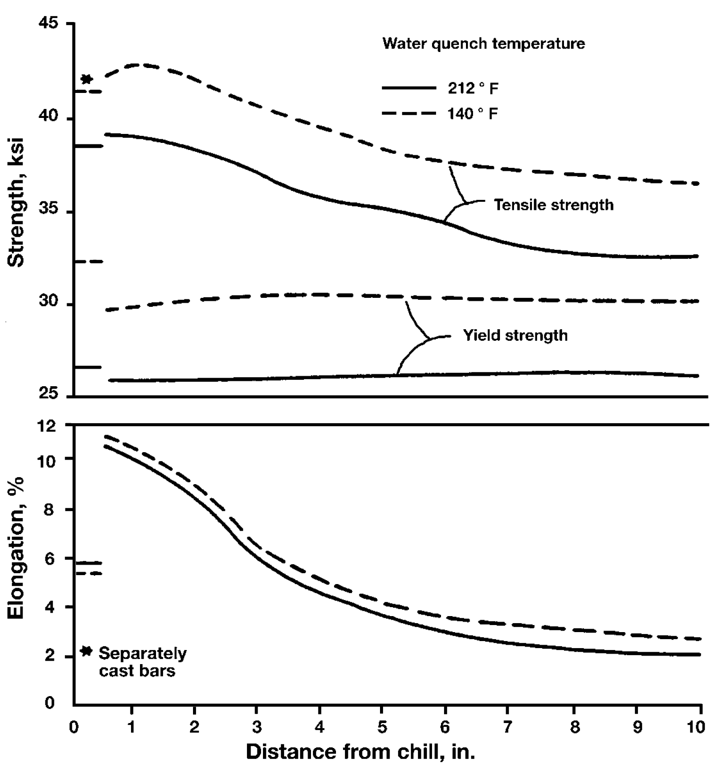

Fig. 7.4 Tensile properties of end-chilled A356-T6 at different quench temperatures. 0.75 in. (19 mm) thick test slab, aged 310 °F (155 °C) for 5 h

The overaged T7 condition is less common than is the T6 temper, but there are good reasons for its use in many applications. Precipitation hardening as practiced for the T6 condition results in reductions of 10 to 35% in residual stresses imposed by quenching. While overaging, by definition, is carrying the aging cycle to a point beyond peak hardness, it is also most often conducted at a higher temperature than employed for the fully hardened condition. A substantial further decrease in residual stresses is associated with the higher-temperature aging treatment. Furthermore, parts become more dimensionally stable as a result of more complete degrowthing, and increased stability in performance is ensured when service involves exposure at elevated temperatures.

7.4 Annealing

Annealing, originally assigned the designation T2, now the O temper, is rarely employed but serves a useful purpose in providing parts with extreme dimensional and physical stability and the lowest level of residual stresses. The annealed condition is also characterized by low strength levels, softness, and correspondingly poor machinability. Typical annealing practices are for relatively short (2 to 4 h) exposures at a minimum temperature of 650 °F (340 °C). Higher-temperature practices are employed for more complete relaxation of residual stresses. The cooling rate from annealing temperature must be controlled in such a way that residual stresses are not reinduced and that resolution effects are avoided. Typical practice is to cool from annealing temperature in the furnace or in still air.

7.5 Stability

Stability is defined as the condition of unchanging structural and physical characteristics as a function of time under service conditions. The metastable T4 condition is subject to hardening, extensive in some alloys and limited in others, at room and higher temperatures. With exposure to elevated temperatures, significant additional physical and mechanical property changes are to be expected. They include dimensional change or growth and changes in susceptibility to corrosion and stress corrosion that can be associated with transitional states in some alloys.

The most stable conditions obtainable are annealed, overaged, aged, and as-cast, in that order. Underaged and solution heat treated parts are least stable.

7.6 Residual Stresses

Thermal treatment not only affects mechanical properties, but also directly influences residual stress levels.

Residual stresses are caused by differences in postsolidification cooling between surface and interior regions. They are induced by cooling from solidification temperature, quenching from solution heat treatment temperature, and by changes in temperature at any intermediate step. Residual stresses are functions of differential cooling rates, section thickness, and material strength. More severe and more rapid temperature change results in large differences in the cooling rates of surface and internal regions of the casting structure. When the part is cooled from elevated temperature, the normal distribution of residual stresses when the part has reached room temperature is compression at the surface and counterbalancing tension in core regions (Fig. 7.5). Increasing thickness and alloy strength increases the magnitude of residual stresses.

Stresses induced by quenching from solution heat treatment temperature are many times more important than casting stresses or stresses imposed in any other conventional process. Decreasing the severity of quench from solution heat treatment results in a lower level of residual stresses but with correspondingly decreased material strength. Air quenching may provide a useful compromise in applications requiring unusual dimensional stability.

Residual stresses may only be relaxed by exposure to elevated temperature followed by slow cooling or by plastic deformation. Plastic deformation, routinely practiced for stress relief in wrought products, has little application in the complex designs of engineered products such as castings, so that stress relief becomes more exclusively a function of thermal treatment. Overaging results in significant reductions in residual stresses, and annealing provides a practical minimum in residual stress levels. The residual stresses retained after annealing or aging is limited by the yield strength of the material at treatment temperature.

7.7 Troubleshooting Heat Treatment Problems

7.7.1 Acceptance Criteria

Mechanical properties that include ultimate tensile strength, yield strength, and elongation are the usual criteria by which material acceptability is determined after heat treatment. Mechanical property limits statistically define normalcy for a given composition cast by a specific process or a composition cast by a specific process that has been heat treated to a specified temper.

Separately cast tensile specimens, poured from the melt from which the casting lot is poured, are typically used for all casting processes. When castings are heat treated, these specimens accompany the castings they represent through all phases of thermal operations. Specifications may also require or rely exclusively on the testing of specimens excised and machined from the casting.

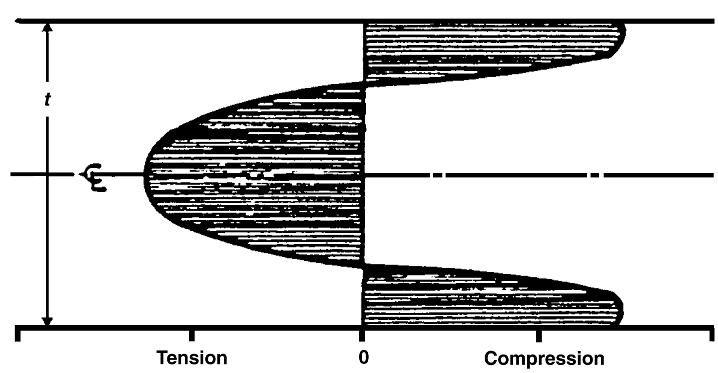

Fig. 7.5 Characteristic residual stress distribution after solution heat treatment and quench. *t*, thickness

Minimum mechanical property limits are usually defined by the terms of general procurement specifications, such as those developed by government agencies and technical societies. These documents specify testing frequency, tensile specimen type, casting lot definitions, testing procedures, and test limits. These requirements may also be separately negotiated.

Brinell hardness (10 mm ball, 500 kg load, 30 s) is only approximately related to yield strength, and while it is used routinely as an easily measurable nondestructive indicator of material condition, it is not normally guaranteed.

Electrical conductivity only approximates the relationship of chemistry, structure, and thermal treatment in cast or cast and heat treated aluminum structures. Electrical conductivity is used in rotors and anodes as an acceptance criterion. It may also be used to estimate susceptibility to stress-corrosion cracking.

7.7.2 Diagnosis

When specified mechanical property limits are not met after heat treatment, analytical procedures and judgments are applied to establish a corrective course of action based on evidence or assumptions concerning the cause of failure. Variations in chemical composition, even within specified limits, can have measurable effects. Metallurgical considerations such as chemical segregation, phase size and distribution, grain and dendrite cell sizes, and the modification or degree of refinement of eutectic and hypereutectic structures alter properties. For heat treated and aged tempers, variables include solution time and temperature, temperature of quenching medium, quench delay, and aging cycle. Annealing times and temperatures and postanneal cooling conditions are important for O temper material.

It is important to establish that the tensile specimens involved were representative and that test procedures conformed to the requirements of applicable test method standards:

- The stress-strain diagram should be used to confirm that test procedures including strain rate were appropriate.
- Failure should not be associated with surface damage such as nicks and scratches or machining errors.
- Specimens may contain nonrepresentative defects.
- The fracture surface should be examined to determine that no anomalous condition contributed to failure.
- The entire fracture must be contained within the center half of the gage length.
- Replacement and retest provisions are defined by specification and standards.

Furnace records and time-temperature charts should be consulted to confirm that specified practices were observed.

The chemical composition of alloys of aluminum is determined by light emission spectroscopy. Quantometers simplify and standardize chemical element concentrations. In some cases, wet chemistry or alternative techniques such as atomic absorption are employed. Less accurate methods including x-ray fluorescence are used to discriminate composition ranges.

Chemical composition is a major variable in mechanical property development. When mechanical properties have failed specification limits and no other practice discrepancies are determined, alloy content should be carefully examined.

The role of trace elements in mechanical property development is important since these are often not separately defined in alloy specifications except as “others each” and “others total.” Sodium and calcium are embrittling in 5xx.0 alloys. Low-temperature-melting elements, such as lead, tin, and bismuth may, under some conditions, form embrittling intergranular networks with similar effects. Insoluble impurity elements are generally responsible for decreases in elongation.

Low concentrations of soluble elements in heat treatable compositions naturally result in the more frequent distribution of mechanical property values in the lower specification range. Element relationships such as Cu-Mg, Si-Mg, Fe-Si, Fe-Mn, and Zn-Cu-Mg are also important considerations in defining the causes of abnormal mechanical property response to thermal treatment. Mechanical property failure may be caused by structural unsoundness and not by inadequate heat treatment. It is not appropriate to believe that unsound castings and tensile specimens will consistently meet specified mechanical property limits. All defects adversely affect strength and elongation. Shrinkage, hydrogen porosity, cracks, inclusions, and other casting-related defects influence mechanical properties adversely, and their effects should be considered before addressing the possibility of heat treatment problems.

The quality of solution heat treatment may be assessed in several ways. There is, of course, the rounding effect on “insoluble phases” that can be observed metallographically and serves as evidence of elevated-temperature exposure. The elimination of microsegregation or coring in many alloys is another indication of elevated-temperature treatment. The effective solution of soluble phases can be determined microscopically. Undissolved solute can be distinguished from the appearance of precipitate that forms at high temperatures and that result from quench delay or an inadequate or incomplete quench by particle size and distribution. There is also a tendency for precipitate that forms as a result of quench delay or inadequate quench to concentrate at grain boundaries as opposed to more normal distribution through the microstructure for properly solution heat treated and aged material.

While the overaged condition is microscopically apparent, underaging is difficult to assess because of the submicroscopic nature of transitional precipitates. Evidence of acceptable aging practice is best obtained from aging furnace records that might indicate errors in the age cycle. While underaging may be corrected by additional aging, for all other heat treatment aberrations, except those associated with objectionable conditions such as high-temperature oxidation or eutectic melting, resolution heat treatment is an acceptable corrective action. Eutectic melting occurs when the eutectic melting temperature is exceeded in solution heat treatment, resulting in characteristic rosettes of resolidified eutectic.

High-temperature oxidation is a misnamed condition of hydrogen diffusion affecting surface layers during solution heat treatment. It results from excessive moisture in the furnace atmosphere, sometimes aggravated by oil, grease, sulfur, or other furnace or casting surface contamination.

There are no technical reasons for discouraging even repeated reheat treatment to obtain acceptable mechanical properties. In the case of aluminum-copper alloys, it is essential that resolution heat

treatment be conducted at a temperature equivalent to or higher than the original practice to ensure effective resolution; however, it should be apparent that when the results of repeated reheat treatment prove to be equally unsatisfactory that other conditions are responsible for mechanical property failure.

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Aluminum Alloy Castings: Properties, Processes, and Applications
J.G. Kaufman, E.L. Rooy, p 69-131
DOI:10.1361/aacp2004p069

CHAPTER 8

Properties and Performance of Aluminum Castings

This chapter takes a detailed look at a wide range of the properties and performance of aluminum casting alloys, including cast aluminum matrix composites, utilizing the following organization of information:

- 8.1 Compositions
- 8.2 Physical properties
- 8.3 Typical and minimum (design) mechanical properties
    - 8.3.1 Typical properties
    - 8.3.2 Design properties (including MMPDS/MIL-HDBK-5)
    - 8.3.3 Effects of subzero and elevated temperatures
    - 8.3.4 Impact of emerging technologies and premium practices on properties
- 8.4 Fatigue resistance
- 8.5 Fracture resistance
- 8.6 Subcritical crack growth
- 8.7 Corrosion resistance
- 8.8 Properties of aluminum matrix composites

8.1 Compositions and Influence of Composition on Characteristics

The compositions of commercial aluminum casting alloys are given in Chapter 2, Table 2.1 (Ref 1, 2).

A summary of the major characteristics of the individual alloys is presented in Table 8.1.

8.2 Physical Properties of Aluminum Casting Alloys

The physical properties of aluminum casting alloys at room temperature are summarized in Table 8.2 (Ref 3–7). Alloy constants permitting the calculation of the coefficients of thermal expansion over various ranges of temperature are provided in Table 8.3.

The effect of elements in and out of solid solution on the resistivity of aluminum casting alloys is illustrated by the data in Table 8.4 (Ref 8).

The densities and moduli of elasticity of all aluminum alloys, including castings, are directly dependent on the alloying content and those properties of the alloying elements themselves. The dependence is such that these properties may be estimated for alloys for which they have been measured directly by summing the percentages of each element multiplied by their own density and/or moduli respectively (i.e., the rule of averages). Table 8.5 is a summary of the densities and average moduli of elasticity of aluminum and the more commonly used alloying elements to aid in such estimates. Values calculated in this manner should be considered estimates, and care should be taken to note the exceptions to the rule for modulus, for example, magnesium, for which the effect is greater than would be expected based on its modulus alone.

The damping characteristics of two aluminum casting alloys, 319.0 and 356.0, as determined in cantilever-beam vibration tests (Ref 11), are presented in Fig. 8.1, where they are compared with the band for wrought alloys. It is clear that the damping characteristics of casting alloys in terms of the log decrement of decay from these tests are in the same broad range as those of the wrought alloys. Data for aluminum wrought alloys with cladding are included in the figure to indicate that 1xx.0 castings and others with very low yield strengths may have appreciably higher damping capacity than the typical 3xx.0 castings.

The growth characteristics of a number of aluminum casting alloys are represented by the curves in Data Set 2. Growth, or more appropriately, dimensional change with time that may be contractive as well as expansive, occurs as a result of microstructural phase changes, principally precipitation from solid solution that occurs with time in service, especially in elevated-temperature applications. Growth is an important consideration for parts for which close dimensional tolerances are a requirement.

Table 8.1 Relative casting and finishing characteristics of cast aluminum alloys

Ratings: 1, excellent; 2, very good; 3, good; 4, fair; 5, poor.

		Casting characteristics					Finishing characteristics				Anodizing		Performance characteristics		
Alloy	Type of casting	Resistance to hot cracking	Shrinkage	Fluidity/ die filling capacity	Pressure tightness	Anti-soldering to die	Machin-ability	Weldability	Polish-ability	Electro-platibility	Appearance	Protection	Corrosion resistance	Elevated-temperature strength	Resistance to wear
201.0	S, P	4	4	3	3	. . .	1	4	1	. . .	2	2	4	1	. . .
204.0	S	4	. . .	3	3	. . .	1	4	2	1	3	4	4	1	. . .
208.0	S	2	2	2	2	. . .	3	3	3	1	3	3	4	3	. . .
213.0	S, P	3	3	2	3	. . .	2	2	. . .	. . .	. . .	. . .	4	1	. . .
222.0	S, P	4	4	3	4	. . .	1	3	2	1	3	3	4	1	. . .
238.0	P	2	3	2	2	. . .	2	3	. . .	. . .	. . .	. . .	4	. . .	. . .
240.0	S, P	4	4	3	4	. . .	3	4	. . .	. . .	. . .	4	4	. . .	
242.0	S	4	3	4	4	. . .	2	3	2	1	3	4	4	1	. . .
A242.0	S	4	4	3	4	. . .	2	3	2	. . .	3	. . .	4	2	. . .
295.0	S	4	4	4	3	. . .	2	2	2	. . .	2	3	4	3	. . .
296.0	P	4	3	4	3	. . .	3	4	2	. . .	3	. . .	4	2	. . .
308.0	P	2	2	2	2	. . .	3	3	3	. . .	4	. . .	3	3	. . .
319.0	S, P	2	2	2	2	. . .	3	2	4	3	4	3	3	3	. . .
328.0	S	1	. . .	1	2	. . .	3	1	3	. . .	4	2	3	2	. . .
332.0	P	1	2	1	2	. . .	3	2	4	3	4	. . .	3	1	. . .
333.0	P	1	1	2	2	. . .	4	3	3	3	4	. . .	3	2	. . .
336.0	P	1	2	2	3	. . .	3	2	4	4	4	. . .	3	1	. . .
354.0	P	1	1	1	1	. . .	3	2	4	2	4	. . .	3	2	. . .
355.0	S	1	1	1	1	. . .	3	2	3	1	4	2	3	2	. . .
C355.0	S, P	1	1	1	1	. . .	3	2	3	1	4	2	3	2	. . .
356.0	S, P	1	1	1	1	. . .	3	2	4	1	4	2	2	3	. . .
A356.0	S, P	1	1	1	1	. . .	3	2	4	1	4	2	2	3	. . .
357.0	S, P	1	1	1	1	. . .	3	2	4	1	4	2	2	3	. . .
A357.0	S, P	1	1	1	1	. . .	3	2	4	1	4	2	2	2	. . .
359.0	S, P	1	1	1	1	. . .	3	2	4	1	4	. . .	3	. . .	. . .
360.0	D	1	1	3	2	2	3	. . .	3	2	3	3	2	1	2
A360.0	D	1	1	3	2	2	3	. . .	3	2	3	3	3	1	2
380.0	D	2	1	2	2	1	3	. . .	3	1	4	3	3	3	4
A380.0	D	2	2	2	2	1	3	. . .	3	1	4	3	3	3	4
383.0	D	1	. . .	1	2	2	2	. . .	3	1	3	3	3	2	2
384.0	D	2	2	1	3	2	4	. . .	3	2	4	4	3	2	2
390.0	D	3	2	1	4	2	5	. . .	5	3	5	3	3	3	1
A390.0	S, P	3	3	3	3	2	2	4	5	3	5	. . .	4	3	. . .
B390.0	D	4	. . .	1	4	2	5	. . .	5	3	5	. . .	5	3	. . .
392.0	D	4	. . .	1	3	2	5	. . .	5	3	5	. . .	2	3	. . .
413.0	D	1	2	1	1	1	4	. . .	5	3	5	5	2	3	3
A413.0	D	1	. . .	1	1	1	4	. . .	5	3	5	. . .	. . .	. . .	. . .
443.0	S, P	1	1	1	1	. . .	3	4	4	. . .	4	2	2	4	. . .
A443.0	S	1	1	1	1	. . .	3	4	4	. . .	4	2	2	4	
B443.0	S	1	1	1	1	. . .	3	4	4	. . .	4	2	2	4	. . .
C443.0	D	3	3	4	3	4	5	. . .	4	2	4	2	2	4	4
A444.0	S, P	1	1	1	1	. . .	3	1	4	. . .	4	. . .	2	4	. . .
511.0	S	4	5	4	5	. . .	1	4	2	. . .	2	. . .	1	3	. . .
512.0	S, P	3	4	4	4	. . .	1	4	2	. . .	2	. . .	1	3	. . .
513.0	P	4	5	4	4	. . .	1	5	1	. . .	1	. . .	1	3	. . .
514.0	S	4	5	4	5	. . .	1	4	1	. . .	1	1	1	3	. . .
518.0	D	5	5	5	5	5	1	. . .	1	5	1	1	1	4	4
520.0	S	2	5	4	5	. . .	1	5	1	. . .	1	1	1	5	. . .
535.0	S	4	5	4	5	. . .	1	3	1	. . .	1	1	1	3	. . .
A535.0	S	4	5	4	4	. . .	1	4	1	. . .	1	. . .	1	3	. . .
B535.0	S	4	5	4	4	. . .	1	4	1	. . .	1	. . .	1	3	. . .
705.0	S	5	4	4	4	. . .	. . .	4	2	. . .	2	2	2	4	. . .
707.0	S	5	4	4	4	. . .	1	4	2	. . .	2	2	2	4	. . .
710.0	S	5	3	4	4	. . .	1	4	2	. . .	2	3	2	4	. . .
711.0	S, P	5	4	5	3	. . .	1	3	1	. . .	1	3	3	5	. . .
712.0	S	4	4	3	4	. . .	1	4	2	. . .	2	3	3	4	. . .
713.0	S	4	4	3	3	. . .	1	3	1	. . .	1	3	2	4	. . .
771.0	S, P	4	4	3	3	. . .	1	. . .	1	. . .	1	2	2	4	. . .
772.0	S, P	4	4	3	3	. . .	1	. . .	1	. . .	1	2	2	4	. . .
850.0	S, P	4	4	4	4	. . .	1	4	3	. . .	. . .	5	3	4	. . .
851.0	S, P	4	4	4	4	. . .	1	4	3	. . .	. . .	5	3	5	. . .
852.0	S, P	4	4	4	4	. . .	1	4	3	. . .	. . .	5	3	5	

Source: Ref 3–5

8.3 Typical and Minimum Mechanical Properties of Aluminum Alloy Castings

The typical and minimum (design) mechanical properties of aluminum casting alloys are presented and discussed in the following sections:

- 8.3.1 Published typical mechanical properties
- 8.3.2 Published minimum (design) mechanical properties
- 8.3.3 Effects of subzero and elevated temperatures on mechanical properties
- 8.3.4 Influence of premium practices and emerging casting technologies on mechanical properties

8.3.1 Published Typical Mechanical Properties

The published aluminum industry typical mechanical properties of aluminum casting alloys are presented in Table 8.6 in English units and in Table 8.7 in metric units (Ref 3–7).

In using the values from Table 8.6 and 8.7, one should bear in mind that the published typical values are normally based on the analysis of the results of separately cast test bars (Appendix 3, Fig. A3.1), not of specimens taken from actual cast components. The casting practices for separately cast test bars are typically more uniform and controlled than for the broad array of cast parts, and so the published typical values may be higher than can be realistically expected from individual cast parts. The industry guideline is that the strengths of actual cast parts may be as low as 75% of the values for separately cast test bars.

In these tables, the typical properties are defined as the average of the range for all compositions of the respective alloy and temper. In most cases, the metric values are converted directly from the English values by multiplying by the appropriate conversion factors and rounding to the nearest megapascal (MPa).

Published typical stress-strain curves for a variety of aluminum alloys are presented in Data Set 3 (Ref 12).

8.3.2 Published Minimum and Design Mechanical Properties

The published aluminum industry specification minimum mechanical properties of aluminum casting alloys in both English and metric units are presented in Table 8.8 (Ref 3–7).

These properties are consistent with the specified minimum tensile requirements cited in the several ASTM standards as published in the *Annual Book of ASTM Standards,* Volume 02.02, namely:

ASTM designation	Title
B 26/B 26M	Standard Specification for Aluminum Alloy Sand Castings
B 85	Standard Specification for Aluminum Alloy Die Castings
B 108	Standard Specification for Aluminum Alloy Permanent Mold Castings
B 618	Standard Specification for Aluminum Alloy Investment Castings
B 686	Standard Specification for Aluminum Alloy Castings, High-Strength

It is important to note that there are no published industry statistically reliable minimum values for die castings of any alloy. This reflects the fact that the properties of individual cast parts may vary rather widely depending on their configuration and the specific casting process. It is recommended that users of aluminum die castings plan to carry out a statistical analysis of the properties of the specific cast part they intend to use as part of the design program.

As with typical properties, it is important to keep in mind that, except where explicitly stated, the specification minimum properties are based on tests of separately cast test bars (i.e., cast at the same time as the specific cast parts). Thus it is to be expected that in many if not all locations in specific cast parts, the properties may be lower than those determined from the separately cast test bars. The industry practice is to consider that the properties of actual conventional castings may be as low as 75% of the cast test bar specification values.

Also, as with the typical properties of aluminum castings, the metric minimum values have been created by converting directly from the English values by multiplying by the appropriate conversion factors and rounding to the nearest megapascal (MPa). It may be noted that this situation is different than for wrought aluminum alloy products, for which hard metric minimum values (i.e., calculated from the original metric test data and rounded) have been determined.

8.3.3 Effects of Subzero and Elevated Temperatures on Mechanical Properties

The published typical tensile properties of several aluminum casting alloys at temperatures as high as 700 °F (370 °C) for holding times as long as 10,000 h are presented in Data Set 4 (Ref 14). For some alloys, data are also included for room temperature after the alloys have been exposed to extended heating at temperatures up to 500 °F (260 °C). Also included where available are data at subzero temperatures as low as –452 °F (–270 °C), near absolute zero. Creep properties are presented in Data Set 5 (also from Ref 14).

Like most other aluminum alloys, the casting alloys have not only higher strengths but also higher elongations at subzero temperatures than at room temperature. While data are available for only one alloy (A356.0-T6) at temperatures below –320 °F (–196 °C), it is clear that this trend continues at lower temperatures, essentially to absolute zero. Aluminum casting alloys may be used under arctic conditions and for cryogenic applications without any fear of low-ductility or brittle fracture.

The effects of temperatures above room temperature also parallel expectations from other aluminum alloys. Typically, as temperature increases above about 212 °F (100 °C), strengths decrease at an increasing rate until they level out around 500 to 600 °F (260 to 315 °C). Strengths also decrease with increasing time at tempera-

Table 8.2 Typical physical properties of cast aluminum alloys

Metric unit values generally derived from engineering/English unit values

Alloy	Temper	Density, lb/in.^{3}	Density, g/cm^3	Specific gravity	Average coefficient of thermal expansion, 68–212 °F, 10^{-6}/°F	Average coefficient of thermal expansion, 20–100 °C, 10^{-6}/°C	Approx melting range(a), °F	Approx melting range(a), °C	Thermal conductivity, At 77 °F, Btu · in./h · ft^2 · °F	Thermal conductivity, At 25 °C, W/m · K
Sand casting										
100.0(c)	F	0.096	2.70	2.70	12.8	22.6	970–1160	520–630	1155	168
201.0(d)	T6	0.101	2.80	2.80	10.7	19.3	1060–1200	570–650	840	121
	T7	0.101	2.80	2.80	10.7	19.3	1060–1200	570–650	840	121
	T43	0.101	2.80	2.80	10.7	19.3	1060–1200	570–650	. . .	. . .
204.0	T4	0.101	2.80	2.80	10.7	19.3	1060–1200	570–650	840	121
A206.0	T4	0.101	2.80	2.80	10.7	19.3	. . .	. . .	. . .	. . .
	T6	0.101	2.80	2.80	10.7	19.3	. . .	. . .	640	92
208.0	F	0.101	2.80	2.80	12.2	22.0	970–1160	520–630	840	121
222.0	F	0.107	2.95	2.95	12.3	22.1	970–1160	520–630	925	133
	O	0.107	2.95	2.95	12.3	22.1	970–1160	520–630	1095	158
	T61	0.101	2.95	2.95	12.3	22.1	970–1160	520–630	895	129
224.0	T62	0.102	2.81	2.81	. . .	. . .	1020–1190	550–645	810	117
	T72	0.102	2.81	2.81	. . .	. . .	1020–1190	550–645	. . .	. . .
240.0	F	0.100	2.78	2.78	12.3	22.1	950–1110	515–605	665	96
242.0	F	0.102	2.81	2.81	12.6	22.7	990–1175	525–635	. . .	. . .
	O	0.102	2.81	2.81	12.6	22.7	990–1175	525–635	925	133
	T571	0.102	2.81	2.81	12.6	22.7	990–1175	525–635	925	133
	T61	0.102	2.81	2.81	12.6	22.7	990–1175	525–635	925	133
	T77	0.102	2.81	2.81	12.6	22.7	990–1175	525–635	1040	150
A242.0	T75	0.102	2.81	2.81	12.6	22.7	990–1175	525–635	. . .	. . .
295.0	T4	0.102	2.81	2.81	12.7	22.9	970–1190	520–645	955	138
	T6	0.102	2.81	2.81	12.7	22.9	970–1190	520–645	955	138
	T62	0.102	2.81	2.81	12.7	22.9	970–1190	520–645	980	141
	T7	0.102	2.81	2.81	12.7	22.9	970–1190	520–645	. . .	. . .
319.0	F	0.101	2.79	2.79	11.9	21.4	960–1120	520–605	780	112
	T5	0.101	2.79	2.79	11.9	21.4	960–1120	520–605	. . .	. . .
	T6	0.101	2.79	2.79	11.9	21.4	960–1120	520–605	. . .	. . .
328.0	F	0.098	2.70	2.70	11.9	21.4	1025–1105	555–595	665	96
	T6	0.098	2.70	2.70	11.9	21.4	1025–1105	555–595		
355.0	F	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	. . .	. . .
	T51	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1155	166
	T6	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1010	145
	T61	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1010	145
	T62	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1010	145
	T7	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1125	162
	T71	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1040	150
C355.0	T6	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1040	150
356.0	F	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615	. . .	. . .
	T51	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615	1155	166
	T6	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615	1040	150
	T7	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615	1110	160
	T71	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615	. . .	. . .
A356.0	F	0.097	2.67	2.67	11.9	21.4	1035–1135	560–610	. . .	. . .
	T51	0.097	2.67	2.67	11.9	21.4	1035–1135	560–610	. . .	. . .
	T6	0.097	2.67	2.67	11.9	21.4	1035–1135	560–610	1040	150
	T61	0.097	2.67	2.67	11.9	21.4	1035–1135	560–610	1040	150
	T71	0.097	2.67	2.67	11.9	21.4	1035–1135	560–610	. . .	. . .
357.0	F	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	1040	150
	T51	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	. . .	. . .
	T6	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	1040	150
	T7	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	. . .	. . .
	T6	0.097	2.67	2.67	11.9	21.4	1035–1135	555–610	1100	158
	T61	0.097	2.67	2.67	11.9	21.4	1035–1135	555–610	1040	150

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

Electrical conductivity(b)				Electrical resistivity		Specific heat		
At 68 °F		At 25 °C						
Volume %IACS	Weight %IACS	Volume MS/m	Weight MS/m	At 68 °F Ohm-Cir.mil/ft	At 20 °C Ohm-mm^2/m	At 68 °F Btu/lb · °F	At 20 °C J/kg · °C	Poisson's ratio
Sand casting (continued)								
54	177	31	103	19	0.032	0.210	879	0.33
30	99	17	57	35	0.057	0.220	922	0.33
33	108	19	63	32	0.052	0.220	922	0.33
...	...	...	...	...	...	0.220	922	0.33
29	95	17	55	36	0.059	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
31	102	18	59	34	0.056	0.230	963	0.33
34	112	20	65	31	0.051	0.230	963	0.33
41	135	24	78	25	0.042	0.230	963	0.33
33	108	19	63	32	0.052	0.230	963	0.33
30	99	17	57	35	0.057	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
23	76	13	44	45	0.075	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
33	108	19	63	32	0.052	0.230	963	0.33
34	112	20	65	31	0.051	0.230	963	0.33
33	108	19	63	32	0.052	0.230	963	0.33
38	125	22	73	27	0.045	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
35	115	20	67	30	0.049	0.230	963	0.33
35	115	20	67	30	0.049	0.230	963	0.33
35	115	20	67	30	0.049	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
28	92	16	53	37	0.061	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
30	99	17	57	35	0.057	0.230	963	0.33
...						0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
43	141	25	82	24	0.040	0.230	963	0.33
38	125	22	73	27	0.045	0.230	963	0.33
37	122	21	71	28	0.047	0.230	963	0.33
38	125	22	73	27	0.045	0.230	963	0.33
42	138	24	80	25	0.041	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
43	141	25	82	24	0.040	0.230	963	0.33
40	131	23	76	26	0.043	0.230	963	0.33
42	138	24	80	25	0.041	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
40	131	23	76	26	0.043	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
40	131	23	76	26	0.043	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

Alloy	Temper	Density, lb/in.^{3}	Density, g/cm^3	Specific gravity	Average coefficient of thermal expansion, 68–212 °F, 10^{-6}/°F	Average coefficient of thermal expansion, 20–100 °C, 10^{-6}/°C	Approx melting range(a), °F	Approx melting range(a), °C	Thermal conductivity, At 77 °F Btu · in./h · ft^2 · °F	Thermal conductivity, At 25 °C W/m · K
Sand casting (continued)										
359.0	T6	0.097	2.67	2.67	11.6	20.9	1045–1115	565–600	955	138
	T62	0.097	2.67	2.67	11.6	20.9	1045–1115	565–600	...	...
443.0	F	0.097	2.69	2.69	12.3	22.1	1065–1170	575–630	1010	145
	O	0.097	2.69	2.69	12.3	22.1	1065–1170	575–630	1125	162
B443.0	F	0.097	2.69	2.69	12.3	22.1	1065–1170	575–630	1010	145
A444.0	F	0.097	2.68	2.68	12.1	21.8	1070–1170	575–630	1095	158
	T4	0.097	2.68	2.68	12.1	21.8	1070–1170	575–630	1100	158
511.0	F	0.100	2.66	2.66	13.1	23.6	1090–1185	590–640	980	141
512.0	F	0.096	2.65	2.65	12.7	22.9	1090–1170	590–630	1010	145
514.0	F	0.096	2.65	2.65	13.4	24.1	1110–1185	600–640	954	137
520.0	T4	0.093	2.57	2.57	13.7	24.7	840–1120	450–600	605	87
535.0	F	0.095	2.62	2.62	13.1	23.6	1020–1165	550–630	695	100
	T5	0.095	2.62	2.62	13.1	23.6	1020–1165	550–630	...	...
A535.0	F	0.090	2.54	2.54	13.4	24.1	1020–1150	550–620	695	100
705.0	F	0.100	2.76	2.76	13.1	23.6	1105–1180	600–640	720	104
707.0	F	0.100	2.77	2.77	13.2	23.8	1085–1165	585–630	720	104
	T5	0.100	2.77	2.77	13.2	23.8	1085–1165	585–630	...	...
	T7	0.100	2.77	2.77	13.2	23.8	1085–1165	585–630	...	...
710.0	F	0.102	2.81	2.81	13.4	24.1	1105–1195	600–650	955	138
	T5	0.102	2.81	2.81	13.4	24.1	1105–1195	600–650	...	...
712.0	F	0.101	2.81	2.81	13.7	24.7	1135–1200	600–640	1100	158
	T5	0.101	2.81	2.81	13.7	24.7	1135–1200	600–640	...	...
713.0	F	0.100	2.81	2.81	13.4	24.1	1100–1180	595–630	1070	154
	T5	0.100	2.81	2.81	13.4	24.1	1100–1180	595–630	...	...
771.0	F	0.102	2.81	2.81	13.7	24.7	1120–1190	550–645	955	138
	T5	0.102	2.81	2.81	13.7	24.7	1120–1190	550–645	...	...
	T52	0.102	2.81	2.81	13.7	24.7	1120–1190	550–645	...	...
	T53	0.102	2.81	2.81	13.7	24.7	1120–1190	550–645	...	...
	T6	0.102	2.81	2.81	13.7	24.7	1120–1190	550–645	...	...
	T71	0.102	2.81	2.81	13.7	24.7	1120–1190	550–645	...	...
850.0	T5	0.104	2.88	2.88	13.0	23.4	435–1200	225–650	1290	186
851.0	T5	0.103	2.83	2.83	12.6	22.7	440–1165	230–630	1155	166
852.0	T5	0.104	2.88	2.88	12.9	23.2	400–1175	210–635	1215	175
Permanent mold casting										
100.0	F	0.096	2.70	2.70	12.8	22.6	970–1160	520–630	1165	168
201.0	T6	0.101	2.80	2.80	10.7	19.3	1060–1200	570–650	840	121
	T7	0.101	2.80	2.80	10.7	19.3	1060–1200	570–650	840	121
	T43	0.101	2.80	2.80	10.7	19.3	1060–1200	570–650	...	...
204.0	T4	0.101	2.80	2.80	10.7	19.3	1060–1200	570–650	695	100
A206.0	T4	0.101	2.80	2.80	10.7	19.3	...	...	...	...
	T6	0.101	2.80	2.80	10.7	19.3	...	...	840	121
	T7	0.101	2.80	2.80	10.7	19.3	...	...	...	...

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

Electrical conductivity(b)				Electrical resistivity		Specific heat		
At 68 °F		At 25 °C						
Volume %IACS	Weight %IACS	Volume MS/m	Weight MS/m	At 68 °F Ohm-Cir.mil/ft	At 20 °C Ohm-mm^2/m	At 68 °F Btu/lb · °F	At 20 °C J/kg · °C	Poisson's ratio
Sand casting (continued)								
35	115	20	67	30	0.049	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
37	122	21	71	28	0.047	0.230	963	0.33
42	138	24	80	25	0.041	0.230	963	0.33
37	122	21	71	28	0.047	0.230	963	0.33
41	135	24	78	25	0.042	0.230	963	0.33
...	...	...	...	...	...	0.230	963	
36	118	21	69	29	0.048	0.230	963	0.33
38	125	22	73	27	0.045	0.230	963	0.33
35	115	20	67	30	0.049	0.230	963	0.33
21	69	12	40	50	0.082	0.230	963	0.33
23	76	13	44	45	0.075	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
23	76	13	44	45	0.075	0.230	963	0.33
25	79	15	46	43	0.071	0.230	963	0.33
25	79	15	46	43	0.071	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
35	111	20	64	31	0.051	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
35	111	20	64	31	0.051	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
30	95	17	55	36	0.059	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
37	117	21	68	29	0.048	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
47	154	27	90	22	0.037	0.230	963	0.33
43	141	25	82	24	0.040	0.230	963	0.33
45	148	26	86	23	0.038	0.230	963	0.33
Permanent mold casting (continued)								
54	177	31	103	19	0.032	0.210	879	0.33
30	90	52	57	35	0.057	0.230	963	0.33
33	108	57	63	32	0.052	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
24	79	14	46	43	0.072	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

		Density			Average coefficient of thermal expansion		Approx melting range(a)		Thermal conductivity	
Alloy	Temper	lb/in.^{3}	g/cm^3	Specific gravity	68–212 °F, 10^{-6}/°F	20–100 °C, 10^{-6}/°C	°F	°C	At 77 °F Btu · in./h · ft^2 · °F	At 25 °C W/m · K
Permanent mold casting (continued)										
208.0	F	0.101	2.79	2.79	12.4	22.3	970–1160	520–630	865	125
	T6	0.101	2.79	2.79	12.4	22.3	970–1160	520–630	. . .	. . .
	T7	0.101	2.79	2.79	12.4	22.3	970–1160	520–630	. . .	. . .
213.0	F	0.110					970–1160	520–630	. . .	. . .
222.0	F	0.107	2.95	2.95	12.3	22.1	970–1160	520–630	925	133
	T551	0.107	2.95	2.95	12.3	22.1	970–1160	520–630	. . .	. . .
	T52	0.107	2.95	2.95	12.3	22.1	970–1160	520–630	. . .	. . .
	T61	0.107	2.95	2.95	12.3	22.1	970–1160	520–630	895	129
238.0	F	0.110	2.95	2.95	11.9	21.4	945–1110	510–600	720	104
242.0	T571	0.102	2.81	2.81	12.6	22.7	990–1175	525–635	925	133
	T61	0.102	2.81	2.81	12.6	22.7	990–1175	525–635	925	133
	T77	0.102	2.81	2.81	12.6	22.7	990–1175	525–635	1040	150
A249.0	T63	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
296.0	T4	0.101	2.80	2.80	12.2	22.0	970–1170	520–630	925	133
	T6	0.101	2.80	2.80	12.2	22.0	970–1170	520–630	925	133
	T7	0.101	2.80	2.80	12.2	22.0	970–1170	520–630	. . .	. . .
308.0	F	0.101	2.79	2.79	11.9	21.4	970–1135	520–615	1010	145
319.0	F	0.101	2.79	2.79	11.9	21.4	960–1120	520–605	780	112
	T6	0.101	2.79	2.79	11.9	21.4	960–1120	520–605	. . .	. . .
324.0	F	0.096	2.67	2.67	11.9	21.4	1010–1120	545–605	1070	154
	T5	0.096	2.67	2.67	11.9	21.4	1010–1120	545–605	. . .	. . .
	T62	0.096	2.67	2.67	11.9	21.4	1010–1120	545–605	. . .	. . .
328.0	F	0.098	2.70	2.70	11.9	21.4	1025–1105	520–600	840	121
	T6	0.098	2.70	2.70	11.9	21.4	1025–1105	520–600	. . .	. . .
332.0	T5	0.100	2.76	2.76	11.5	20.7	970–1080	525–585	720	104
333.0	F	0.100	2.77	2.77	11.4	20.5	960–1085	520–585	720	104
	T5	0.100	2.77	2.77	11.4	20.5	960–1085	520–585	810	117
	T6	0.100	2.77	2.77	11.4	20.5	960–1085	520–585	810	117
	T7	0.100	2.77	2.77	11.4	20.5	960–1085	520–585	955	138
336.0	T551	0.098	2.72	2.72	11.0	19.8	1000–1050	540–570	810	117
	T65	0.098	2.72	2.72	11.0	19.8	1000–1050	540–570	. . .	. . .
354.0	T61	0.098	2.71	2.71	11.6	20.9	1000–1105	540–600	866	125
	T62	0.098	2.71	2.71	11.6	20.9	1000–1105	540–600	. . .	. . .
355.0	F	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620		
	T51	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1155	166
	T6	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1040	150
	T61	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1010	145
	T62	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1010	145
	T7	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1125	162
	T71	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1040	150
C355.0	T6	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	. . .	. . .
	T61	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	1010	145
	T62	0.098	2.71	2.71	12.4	22.3	1015–1150	550–620	. . .	. . .
356.0	F	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615		
	T51	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615	1155	166
	T6	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615	1040	150
	T7	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615	1110	160
	T71	0.097	2.68	2.68	11.9	21.4	1035–1135	560–615	. . .	. . .
A356.0	F	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	. . .	. . .
	T51	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	. . .	. . .
	T6	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	1040	150
	T61	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	. . .	. . .

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

Electrical conductivity(b) At 68 °F Volume %IACS	Electrical conductivity(b) At 68 °F Weight %IACS	Electrical conductivity(b) At 25 °C Volume MS/m	Electrical conductivity(b) At 25 °C Weight MS/m	Electrical resistivity At 68 °F Ohm-Cir.mil/ft	Electrical resistivity At 20 °C Ohm-mm^2/m	Specific heat At 68 °F Btu/lb · °F	Specific heat At 20 °C J/kg · °C	Poisson's ratio
Permanent mold casting (continued)								
31	102	18	59	34	0.056	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
34	112	20	65	31	0.051	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
33	108	19	63	32	0.052	0.230	963	0.33
25	82	15	48	42	0.069	0.230	963	0.33
34	112	20	65	31	0.051	0.230	963	0.33
33	108	19	63	32	0.052	0.230	963	0.33
38	125	22	73	27	0.045	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
33	108	19	63	32	0.052	0.230	963	0.33
33	108	19	63	32	0.052	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
37	122	21	71	28	0.047	0.230	963	0.33
27	89	16	52	39	0.064	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
34	112	20	65	31	0.051	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
30	99	17	57	35	0.057	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
26	85	15	50	40	0.066	0.230	963	0.33
26	85	15	50	40	0.066	0.230	963	0.33
29	95	17	55	36	0.059	0.230	963	0.33
29	95	17	55	36	0.059	0.230	963	0.33
35	115	20	67	30	0.049	0.230	963	0.33
29	95	17	55	36	0.059	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
32	105	19	61	33	0.054	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
						0.230	963	0.33
43	141	25	82	24	0.040	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33
37	122	21	71	28	0.047	0.230	963	0.33
38	125	22	73	27	0.045	0.230	963	0.33
42	138	24	80	25	0.041	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
43	141	25	82	24	0.040	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
. . .						0.230	963	0.33
43	141	25	82	24	0.040	0.230	963	0.33
41	135	24	78	25	0.042	0.230	963	0.33
42	138	24	80	25	0.041	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
. . .	. . .	. . .	. . .	. . .	. . .	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

Alloy	Temper	Density, lb/in.^{3}	Density, g/cm^3	Specific gravity	Average coefficient of thermal expansion, 68–212 °F, 10^{-6}/°F	Average coefficient of thermal expansion, 20–100 °C, 10^{-6}/°C	Approx melting range(a), °F	Approx melting range(a), °C	Thermal conductivity, At 77 °F, Btu · in./h · ft^2 · °F	Thermal conductivity, At 25 °C, W/m · K
Permanent mold casting (continued)										
357.0	F	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	1040	150
	T51	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615		
	T6	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615		
	T7	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615		
A357.0	T6	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	1100	158
	T6	0.097	2.67	2.67	11.9	21.4	1035–1135	560–615	1100	158
359.0	T6	0.097	2.67	2.67	11.6	20.9	1045–1115	565–605	955	138
	T61	0.097	2.67	2.67	11.6	20.9	1045–1115	565–605	...	...
	T62	0.097	2.67	2.67	11.6	20.9	1045–1115	565–605	...	...
443.0	O	0.097	2.69	2.69	12.3	22.1	1065–1170	575–630	1125	162
	F	0.097	2.69	2.69	12.3	22.1	1065–1170	575–630	1010	145
B443.0	F	0.097	2.69	2.69	12.3	22.1	1065–1170	575–630	1010	145
A444.0	F	0.097	2.68	2.68	12.1	21.8	1070–1170	575–630	1100	158
	T4	0.097	2.68	2.68	12.1	21.8	1070–1170	575–630		
513.0	F	0.097	2.68	2.68	13.4	24.1	1075–1180	580–640	925	133
711.0	F	0.103	2.84	2.84	13.1	23.6	1110–1190	600–645	1100	158
850.0	T5	0.104	2.88	2.88	13.0	23.4	435–1200	225–650	1290	186
851.0	T5	0.103	2.83	2.83	12.6	22.7	440–1165	230–630	1155	166
	T6	0.103	2.83	2.83	12.6	22.7	440–1165	230–630	...	...
852.0	T5	0.104	2.88	2.88	12.9	23.2	400–1175	210–635	1215	175
Die casting										
360.0	F	0.095	2.63	2.63	11.6	21.0	1035–1105	557–596	785	113
A360.0	F	0.095	2.63	2.63	11.6	21.0	1035–1105	557–596	785	113
380.0	F	0.099	2.74	2.74	12.2	22.2	1000–1100	540–595	667	96
A380.0	F	0.098	2.71	2.71	12.1	21.8	1000–1100	540–595	667	96
383.0	F	0.099	2.74	2.74	11.7	21.1	960–1080	516–582	667	96
384.0	F	0.102	2.82	2.82	11.6	21.0	960–1080	516–582	667	96
390.0	F	...	...	...	...	...	...	...	...	...
B390.0	F	0.098	2.73	2.73	10.0	18.0	950–1200	510–650	930	134
392.0	F	...	...	...	...	...	...	...	...	...
413.0	F	0.096	2.66	2.66	11.3	20.4	1065–1080	574–582	840	121
A413.0	F	0.096	2.66	2.66	11.9	21.6	1065–1080	574–582	840	121
C443.0	F	0.097	2.69	2.69	12.2	22.0	1065–1170	574–632	985	142
518.0	F	0.093	2.57	2.57	13.4	24.1	995–1150	535–621	667	96

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

Electrical conductivity(b)				Electrical resistivity		Specific heat		
At 68 °F		At 25 °C						
Volume %IACS	Weight %IACS	Volume MS/m	Weight MS/m	At 68 °F Ohm-Cir.mil/ft	At 20 °C Ohm-mm^2/m	At 68 °F Btu/lb · °F	At 20 °C J/kg · °C	Poisson's ratio
Permanent mold casting (continued)								
39	128	23	74	27	0.044	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
39	128	23	74	27	0.044	0.230	963	0.33
35	115	20	67	30	0.049	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
42	138	24	80	25	0.041	0.230	963	
37	122	21	71	28	0.047	0.230	963	0.33
37	122	21	71	28	0.047	0.230	963	0.33
41	135	24	78	25	0.042	0.230	963	0.33
41	135	24	78	25	0.042	0.230	963	0.33
34	112	20	65	31	0.051	0.230	963	0.33
40	127	23	74	27	0.045	0.230	963	0.33
47	154	27	90	22	0.037	0.230	963	0.33
43	141	25	82	24	0.040	0.230	963	0.33
...	...	...	...	...	...	0.230	963	0.33
45	148	26	86	23	0.038	0.230	963	0.33
Die casting (continued)								
30	99	17	57	35	0.057	0.230	963	0.33
29	95	17	55	36	0.059	0.230	963	0.33
27	89	16	52	39	0.064	0.230	963	0.33
23	76	13	44	45	0.075	0.230	963	0.33
23	76	13	44	45	0.075	0.230	963	0.33
22	72	13	42	47	0.078	...	...	0.33
...	...	...	...	...	...	...	...	0.33
27	89	16	52	39	0.064	...	...	0.33
...	...	...	...	...	...	...	...	0.33
31	102	18	59	34	0.056	0.230	963	0.33
31	102	18	59	34	0.056	0.230	963	0.33
37	122	21	71	28	0.047	0.230	963	0.33
24	79	14	46	43	0.072	...	...	0.33

(a) Based on nominal composition of each alloy in thicknesses of 1/4 in. (6 mm) or greater. (b) % IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.3 Alloy constants for calculation of coefficients of thermal expansion for some aluminum casting alloys over various temperature ranges

Alloy	Alloy constant *C*	Alloy	Alloy constant *C*	Alloy	Alloy constant *C*
208.0	0.950	356.0	0.910	511.0	1.005
240.0	0.990	A356.0	0.910	513.0	1.020
242.0	0.955	357.0	0.920	514.0	1.020
295.0	0.970	A357.0	0.920	518.0	1.015
308.0	0.910	359.0	0.900	520.0	1.040
319.0	0.905	360.0	0.890	710.0	1.020
332.0	0.875	A360.0	0.900	711.0	1.000
333.0	0.880	380.0	0.885	712.0	1.010
336.0	0.845	A380	0.895	850.0	0.990
354.0	0.895	413.0	0.860	851.0	0.965
355.0	0.950	C443.0	0.945	852.0	0.985
C355.0	0.950	A444.0	0.920	. . .	. . .

Equations of linear thermal expansion:

1. $L_{t\,(0\text{ to }-320\ °F)} = L_0[1 + C\,(11.74t - 0.00125t^2 - 0.0000248t^3)\,10^{-6}]$
2. $L_{t\,(0\text{ to }1000\ °F)} = L_0[1 + C\,(12.19t + 0.003115t^2)\,10^{-6}]$
3. $L_{t\,(-76\text{ to }212\ °F)} = L_0[1 + C\,(12.08t + 0.003765t^2)\,10^{-6}]$

L_0 = Length at 0 °F
L_t = Length at temperature, t °F, within the range indicated
C = Alloy constant

Constants established from determinations made on alloys in the annealed (O temper) condition. With heat treatable alloys, the application of the above equations and alloy constants is limited to temperatures below 600 °F (315 °C); for such alloys, the alloy constants are approximately 0.015 higher in the heat treated condition and should be applied to temperatures that do not exceed those used in the final aging treatments. For 7xx.x and 8xx.x casting alloys, application is restricted to 400 °F (200 °C). Source: Ref 10

Table 8.4 Effect of elements in and out of solution on resistivity

Element	Maximum solubility in aluminum, %	Average increase in resistivity per wt%(a), μΩ/cm: In solution	Out of solution(b)
Chromium	0.77	4	0.18
Copper	5.65	0.344	0.03
Iron	0.052	2.56	0.058
Lithium	4	3.31	0.68
Magnesium	14.9	0.54(c)	0.22(c)
Manganese	1.82	2.94	0.34
Nickel	0.05	0.81	0.061
Silicon	1.65	1.02	0.088
Titanium	1	2.88	0.12
Vanadium	0.5	3.58	0.28
Zinc	82.8	0.094(d)	0.023(d)
Zirconium	0.28	1.74	0.044

(a) Add increase to the base resistivity for high-purity aluminum: 2.65 μΩ-cm at 20 °C (68 °F) or 2.71 μΩ-cm at 25 °C (77 °F). (b) Limited to about twice the concentration given for the maximum solid solubility, except as noted. (c) Limited to approximately 10%. (d) Limited to approximately 20%

Table 8.5 Densities and elastic moduli of aluminum and aluminum alloying elements

Alloying element	Density: lb/in.^{2}	Density: g/cm^3	Elastic modulus: 10^6 psi	Elastic modulus: GPa
Aluminum	0.0971	2.699	10.0	69
Chromium	0.260	7.19	36.0	248
Copper	0.324	8.96	16.0	128
Iron	0.284	7.87	28.5	208
Magnesium	0.0628	1.74	6.5(a)	44(a)
Manganese	0.268	7.43	23.0	159
Nickel	0.322	8.90	30.0	207
Silicon	0.084	2.33	16.0	110
Tin	0.264	7.30	6.0	44
Titanium	0.164	4.54	16.8	120
Zinc	0.258	7.13	10(b)	69(b)
Zirconium	0.23	6.5	11.0	49

(a) Effect of magnesium is equivalent to approximately 11.0 × 10^6 psi or 75 GPa. (b) The modulus of zinc is not well defined; these values are lower limit estimates.

ture, especially in the intermediate temperature range. Elongations increase with increasing time and/or temperature.

Of the alloys for which data are presented, 201.0-T7 clearly has the superior strengths at elevated temperatures. In fact all of the 2xx.0 alloys hold up rather well at temperatures up to about 400 °F (205 °C) compared to alloys of the other series. It is the influence of the copper content providing the high-temperature resistance of the 2xx.0 series.

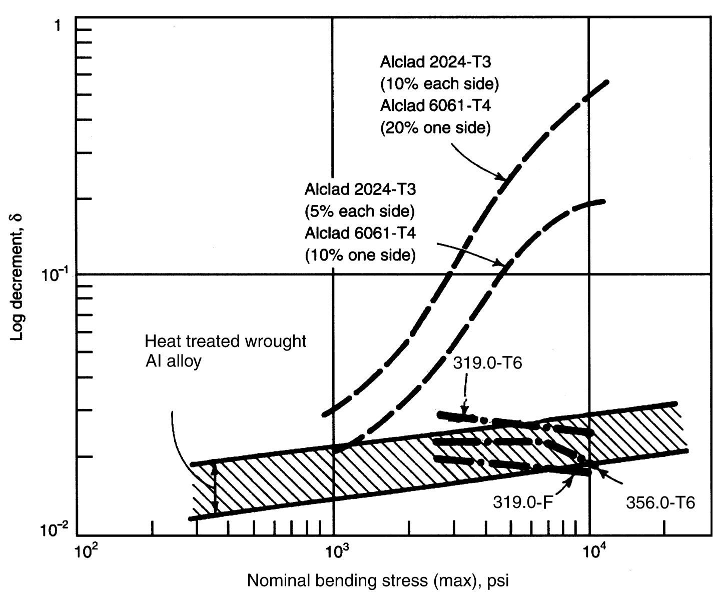

Fig. 8.1 Damping characteristics of 319.0 and 356.0 casting alloys compared with those of wrought alloys, including clad 2024. Source: Ref 11

Table 8.6 Typical mechanical properties of aluminum alloy castings at room temperature (engineering units)

Values are representative of separately cast test bars, not of specimens taken from commercial castings.

		Tension						
Alloy	Temper	Ultimate strength, ksi	Yield strength(a), ksi	Elongation in 2 in. or 4*D*, %	Hardness(b), HB	Shear ultimate strength, ksi	Fatigue ultimate limit(c), ksi	Modulus of elasticity(d), 10^6 psi
Sand casting								
201.0	T6	65	55	8	130	...	...	...
	T7	68	60	6	...	...	14	...
	T43	60	37	17	...	...	...	...
204.0	T4	45	28	6	...	...	...	...
A206.0	T4	51	36	7	...	40	...	...
208.0	F	21	14	3	...	17	11	...
213.0	F	24	15	2	70	20	9	...
222.0	O	27	20	1	80	21	9.5	
	T61	41	40	<0.5	115	32	8.5	10.7
224.0	T72	55	40	10	123	35	9	10.5
240.0	F	34	28	1	90	...	...	...
242.0	F	31	20	1	...	...	...	10.3
	O	27	18	1	70	21	8	10.3
	T571	32	30	1	85	26	11	10.3
	T61	32	20	...	90–120	...	...	10.3
	T77	30	23	2	75	24	10.5	10.3
A242.0	T75	31	...	2	...	...	...	...
295.0	T4	32	16	9	80	26	7	10.0
	T6	36	24	5	75	30	7.5	10.0
	T62	41	32	2	90	33	8	10.0
	T7	29	16	3	55–85	...	...	10.0
319.0	F	27	18	2	70	22	10	10.7
	T5	30	26	2	80	24	11	10.7
	T6	36	24	2	80	29	11	10.7
328.0	F	25	14	1	45–75	...	...	...
	T6	34	21	1	65–95	...	...	...
354.0	T62	55	45	3	...	...	...	...
355.0	F	23	12	3	...	...	...	10.2
	T51	28	23	2	65	22	8	10.2
	T6	35	25	3	80	28	9	10.2
	T61	35	35	1	90	31	9.5	10.2
	T7	38	26	1	85	28	10	10.2
	T71	35	29	2	75	26	10	10.2
C355.0	T6	39	29	5	85	...	...	...
356.0	F	24	18	6	...	...	...	10.5
	T51	25	20	2	60	20	8	10.5
	T6	33	24	4	70	26	8.5	10.5
	T7	34	30	2	75	24	9	10.5
	T71	28	21	4	60	20	8.5	10.5
A356.0	F	23	12	6	...	...	...	10.5
	T51	26	18	3	...	...	...	10.5
	T6	40	30	6	75	...	...	10.5
	T71	30	20	3	...	...	...	10.5
357.0	F	25	13	5	...	...	...	...
	T51	26	17	3	...	...	...	...
	T6	50	43	2	...	...	...	...
	T7	40	34	3	60	...	...	...
A357.0	T6	46	36	3	85	40	12	...
359.0	T62	50	42	5	...	...	16	...
A390.0	F	26	26	<1.0	100	...	...	...
	T5	26	26	<1.0	100	...	...	...
	T6	40	40	<1.0	140	...	13	...

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 10 mm ball. (c) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (d) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.6 (continued)

Alloy	Temper	Tension: Ultimate strength, ksi	Tension: Yield strength(a), ksi	Tension: Elongation in 2 in. or 4*D*, %	Hardness(b), HB	Shear ultimate strength, ksi	Fatigue ultimate limit(c), ksi	Modulus of elasticity(d), 10^6 psi
Sand casting (continued)								
	T7	36	36	<1.0	115	. . .	. . .	. . .
443.0	F	19	8	8	40	14	8	10.3
B443.0	F	17	6	3	25–55	. . .	. . .	. . .
A444.0	F	21	9	9	44	. . .	. . .	. . .
	T4	23	9	12	45			
511.0	F	21	12	3	50	17	8	. . .
512.0	F	20	13	2	50	17	9	. . .
514.0	F	25	12	9	50	20	7	. . .
520.0	T4	48	26	16	75	34	8	. . .
535.0	F	35	18	9	60–90	. . .	. . .	. . .
	T5	35	18	9	60–90	. . .	. . .	. . .
A535.0	F	36	18	9	65	. . .	. . .	. . .
707.0	T5	33	22	2	70–100	. . .	. . .	. . .
	T7	37	30	1	65–95	. . .	. . .	. . .
710.0	F	32	20	2	60–90	. . .	. . .	. . .
	T5	32	20	2	60–90	. . .	. . .	. . .
712.0	F	34	25	4	60–90	. . .	. . .	. . .
	T5	34	25	4	60–90	. . .	. . .	. . .
713.0	F	32	22	3	60–90	. . .	. . .	. . .
	T5	32	22	3	60–90	. . .	. . .	. . .
771.0	T5	32	27	3	70–100	. . .	. . .	. . .
	T52	36	30	2	70–100	. . .	. . .	. . .
	T53	36	27	2	. . .	. . .	. . .	. . .
	T6	42	35	5	75–105	. . .	. . .	. . .
	T71	48	45	2	105–135	. . .	. . .	. . .
850.0	T5	20	11	8	45	14	. . .	10.3
851.0	T5	20	11	5	45	14	. . .	10.3
852.0	T5	27	22	2	65	18	10	10.3
Permanent mold casting								
201.0	T6	65	55	8	130	. . .	. . .	. . .
	T7	68	60	6	. . .	. . .	14	. . .
	T43	60	37	17	. . .	. . .	. . .	. . .
204.0	T4	48	29	8	. . .	. . .	. . .	. . .
A206.0	T4	62	38	17	. . .	42	. . ..	. . .
	T7	63	50	12	. . .	37	. . .	. . .
208.0	T6	35	22	2	75–105	. . .	. . .	. . .
	T7	33	16	3	65–95	. . .	. . .	. . .
213.0	F	30	24	2	85	24	9.5	. . .
222.0	T551	37	35	<0.5	115	30	8.5	10.7
	T52	35	31	1	100	25	. . .	10.7
238.0	F	30	24	2	100	24	. . .	. . .
242.0	T571	40	34	1	105	30	10.5	10.3
	T61	47	42	1	110	35	10	10.3

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 10 mm ball. (c) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (d) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.6 (continued)

Alloy	Temper	Tension: Ultimate strength, ksi	Tension: Yield strength(a), ksi	Tension: Elongation in 2 in. or 4*D*, %	Hardness(b), HB	Shear ultimate strength, ksi	Fatigue ultimate limit(c), ksi	Modulus of elasticity(d), 10^6 psi
Permanent mold casting (continued)								
A249.0	T63	69	60	6	...	...	...	...
296.0	T7	39	20	5	80	30	9	10.1
308.0	F	28	16	2	70	22	13	...
319.0	F	34	19	3	85	24	...	10.7
	T6	40	27	3	95	...	...	10.7
324.0	F	30	16	4	70	...	...	...
	T5	36	26	3	90	...	...	...
	T62	45	39	3	105	...	...	...
332.0	T5	36	28	1	105	...	...	...
328.0	T6	34	21	1	65–95	...	...	...
333.0	F	34	19	2	90	27	15	...
	T5	34	25	1	100	27	12	...
	T6	42	30	2	105	33	15	...
	T7	37	28	2	90	28	12	...
336.0	T551	36	28	1	105	28	14	...
	T65	47	43	1	125	36	...	...
354.0	T61	52	39	6	...	...	19	...
	T62	55	45	3	...	...	...	...
355.0	F	27	15	4	...	...	...	10.2
	T51	30	24	2	75	24	...	10.2
	T6	42	27	4	90	34	10	10.2
	T61	45	40	2	105	36	10	10.2
	T7	40	30	2	85	30	10	10.2
	T71	36	31	3	85	27	10	10.2
C355.0	T6	48	28	8	90	...	...	10.2
	T61	46	34	6	100	...	...	10.2
	T62	48	37	5	100	...	...	10.2
356.0	F	26	18	5	...	...	...	10.5
	T51	27	20	2	...	...	...	10.5
	T6	38	27	5	80	30	13	10.5
	T7	32	24	6	70	25	11	10.5
	T71	25	...	3	60–90	...	...	10.5
A356.0	F	27	13	8	...	...	...	10.5
	T51	29	20	5	...	...	...	10.5
	T6	41	30	12	80	...	...	10.5
357.0	F	28	15	6	...	...	...	...
	T51	29	21	4	...	...	...	...
	T6	52	43	5	100	35	13	...
	T7	38	30	5	70	...	...	...
A357.0	T6	52	42	5	100	35	15	...
359.0	T61	48	37	6	...	...	...	...
	T62	50	42	5	...	...	16	...
A390.0	F	29	29	<1.0	110	...	...	...
	T5	29	29	<1.0	110	...	...	...
	T6	45	45	<1.0	145	...	17	...
	T7	38	38	<1.0	120	...	15	...
443.0	F	23	9	10	45	16	8	10.3
B443.0	F	21	6	6	30–60	...	...	...
A444.0	F	24	11	13	44	...	...	...
	T4	23	10	21	45	16	8	...
513.0	F	27	16	7	60	22	10	...
535.0	F	35	18	8	60–90	...	...	...

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 10 mm ball. (c) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (d) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.6 (continued)

Alloy	Temper	Tension: Ultimate strength, ksi	Tension: Yield strength(a), ksi	Tension: Elongation in 2 in. or 4*D*, %	Hardness(b), HB	Shear ultimate strength, ksi	Fatigue ultimate limit(c), ksi	Modulus of elasticity(d), 10^6 psi
Permanent mold casting (continued)								
705.0	T5	37	17	10	55–75	. . .	. . .	. . .
707.0	T7	45	35	3	80–110	. . .	. . .	. . .
711.0	T1	28	18	7	55–85	. . .	. . .	. . .
713.0	T5	32	22	4	60–90			
850.0	T5	23	11	12	45	15	9	10.3
851.0	T5	20	11	5	45	14	9	10.3
	T6	18	. . .	8	. . .	. . .	. . .	10.3
852.0	T5	32	23	5	70	21	11	10.3
Die casting								
360.0	F	44	25	3	75	28	20	10.3
A360.0	F	46	24	4	75	26	18	10.3
380.0	F	46	23	3	80	28	20	10.3
A380.0	F	47	23	4	80	27	20	10.3
383.0	F	45	22	4	75	. . .	21	10.3
384.0	F	48	24	3	85	29	20	. . .
390.0	F	40.5	35	<1	. . .	. . .	. . .	. . .
B390.0	F	46	36	<1	120	. . .	20	11.8
392.0	F	42	39	<1	. . .	. . .	. . .	. . .
413.0	F	43	21	3	80	25	19	10.3
A413.0	F	42	19	4	80	25	19	. . .
C443.0	F	33	14	9	65	29	17	10.3
518.0	F	45	28	5	80	29	20	. . .

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 10 mm ball. (c) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (d) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

8.3.4 Influence of Premium Practices and Emerging Casting Technologies on Mechanical Properties

Premium Engineered Castings. As noted in Chapter 3, it has been recognized for many years that special care in the application of metal flow and chill practices can lead to superior properties for aluminum casting alloys, and the consistent use of such practices has led to a classification of aluminum castings known as "premium quality" or "premium engineered" castings.

The typical and minimum properties of the more widely used casting alloys developed using this technology are summarized in Tables 8.9 and 8.10, respectively (Ref 8, 15). The minimum properties shown are the design mechanical properties published in MMPDS (previously known as MIL-HDBK-5) and from AMS-A-21180 (previously MIL-A-21180). Note the several levels of control on location and quality of casting, which sometimes greatly influences the published design property.

Both aluminum industry sources and MMPDS/MIL-HDBK-5 define the minimum and/or design properties as the values which the properties of 99% of the lots of a given alloy and temper would equal or exceed, with 95% confidence.

Specification AMS-A-21180 defines the requirements for high-strength aluminum alloy castings. Mechanical properties based on the results of excised or prolongation specimens representing the actual casting rather than separately cast specimens that represent conformance to expected chemistry and heat treatment responses. In most cases, this and other specifications and standards serve only as the guide to separately negotiated requirements. With the passage of time property requirements for premium engineered castings increasingly exceeded those defined by this specification.

Plaster cast low-pressure impellers and rotors that were heavily and directionally chilled routinely exceeded even negotiated property limits. For level and conventionally poured premium engineered castings, consistently meeting mechanical testing requirements was more tenuous when guarantees for tensile properties were 15 to 25% and ductility 60 to 100% higher than the limits

Table 8.7 Typical mechanical properties of aluminum alloy castings at room temperature (metric units)

Values are representative of separately cast test bars, not of specimens taken from commercial castings.

		Tension						
Alloy	Temper	Ultimate strength, MPa	Yield strength(a), MPa	Elongation in 5*D*, %	Hardness(b), HB 500 kg/10 mm	Shear ultimate strength, MPa	Fatigue endurance limit(b), MPa	Modulus of elasticity(c), GPa
Sand casting								
201.0	T6	450	380	8	130	. . .	. . .	. . .
	T7	470	415	6	. . .	. . .	95	. . .
	T43	415	255	17	. . .	. . .	. . .	. . .
204.0	T4	310	195	6	. . .	. . .	. . .	. . .
A206.0	T4	350	250	7	. . .	275	. . .	. . .
208.0	F	145	655	3	. . .	115	75	. . .
213.0	F	165	105	2	70	140	60	. . .
222.0	O	185	140	1	80	145	65	
	T61	285	275	<0.5	115	220	60	74
224.0	T72	380	275	10	123	240	60	73
240.0	F	235	195	1	90	. . .	. . .	. . .
242.0	F	145	140	1	. . .	. . .	. . .	71
	O	185	125	1	70	145	55	71
	T571	220	205	1	85	180	75	71
	T61	220	140	. . .	90–120	. . .	. . .	71
	T77	205	160	2	75	165	70	71
A242.0	T75	215	. . .	2	. . .	. . .	. . .	. . .
295.0	T4	220	110	9	80	180	50	69
	T6	250	165	5	75	205	50	69
	T62	285	220	2	90	230	55	69
	T7	200	110	3	55–85	. . .	. . .	69
319.0	F	185	125	2	70	150	70	74
	T5	205	180	2	80	165	75	74
	T6	250	165	2	80	200	75	74
328.0	F	170	95	1	45–75	. . .	. . .	. . .
	T6	235	145	1	65–95	. . .	. . .	. . .
354.0	T62	380	310	3	. . .	. . .	. . .	. . .
355.0	F	160	85	3	. . .	. . .	. . .	70
	T51	195	160	2	65	150	55	70
	T6	240	170	3	80	195	60	70
	T61	240	240	1	90	215	65	70
	T7	260	180	1	85	195	70	70
	T71	240	200	2	75	180	70	70
C355.0	T6	270	200	5	85	. . .	. . .	. . .
356.0	F	165	125	6	. . .	. . .	. . .	73
	T51	170	140	2	60	140	55	73
	T6	230	165	4	70	180	60	73
	T7	235	205	2	75	165	60	73
	T71	195	145	4	60	140	60	73
A356.0	F	160	85	6	. . .	. . .	. . .	73
	T51	180	125	3	. . .	. . .	. . .	73
	T6	275	205	6	75	. . .	. . .	73
	T71	205	140	3	. . .	. . .	. . .	73
357.0	F	170	90	5	. . .	. . .	. . .	. . .
	T51	180	115	3	. . .	. . .	. . .	. . .
	T6	345	295	2	. . .	. . .	. . .	. . .
	T7	275	235	3	60	. . .	. . .	. . .
A357.0	T6	315	250	3	85	275	85	. . .
359.0	T62	345	290	5	. . .	. . .	110	. . .
A390.0	F	180	180	<1.0	100	. . .	. . .	. . .
	T5	180	180	<1.0	100	. . .	. . .	. . .

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.7 (continued)

Alloy	Temper	Tension: Ultimate strength, MPa	Tension: Yield strength(a), MPa	Tension: Elongation in 5*D*, %	Hardness(b), HB 500 kg/10 mm	Shear ultimate strength, MPa	Fatigue endurance limit(b), MPa	Modulus of elasticity(c), GPa
Sand casting (continued)								
	T6	275	275	<1.0	140	...	90	...
	T7	250	250	<1.0	115	...	...	...
443.0	F	130	55	8	40	95	55	71
B443.0	F	115	40	3	25–55	...	...	...
A444.0	F	145	60	9	43,400	...	...	...
	T4	23	60	12				
511.0	F	145	85	3	50	115	55	...
512.0	F	140	90	2	50	115	60	...
514.0	F	170	85	9	50	140	50	...
520.0	T4	330	180	16	75	235	55	...
535.0	T	240	125	9	60–90	...	...	...
	T5	240	125	9	60–90	...	...	...
A535.0	F	250	125	9	65	...	...	...
707.0	T5	230	150	2	70–100	...	...	...
	T7	255	205	1	65–95	...	...	...
710.0	F	220	140	2	60–90	...	...	...
	T5	220	140	2	60–90	...	...	...
712.0	F	235	170	4	60–90	...	...	...
	T5	235	170	4	60–90	...	...	...
713.0	F	220	150	3	60–90	...	...	...
	T5	220	150	3	60–90	...	...	...
771.0	T5	220	185	3	70–100	...	...	...
	T52	250	205	2	70–100	...	...	...
	T53	250	185	2	...	...	...	...
	T6	290	240	5	75–105	...	...	...
	T71	330	310	2	105–135	...	...	...
850.0	T5	140	75	8	45	95	...	71
851.0	T5	140	75	5	45	95	...	71
852.0	T5	185	150	2	65	125	60	71
Permanent mold casting								
201.0	T6	450	380	8	130	...	...	...
	T7	470	415	6	...	...	95	...
	T43	415	255	17	...	...	...	...
204.0	T4	330	200	8	...	...	...	...
A206.0	T4	430	260	17	...	290	...	...
	T7	435	345	12	...	255	...	...
208.0	T6	240	150	2	75–105	...	...	...
	T7	230	110	3	65–95	...	...	...
213.0	F	205	165	2	85	165	65	...
222.0	T551	255	240	<0.5	115	205	60	74
	T52	240	215	1	100	170	...	74
238.0	F	205	165	2	100	165	...	...
242.0	T571	275	235	1	105	205	70	74
	T61	325	290	1	110	450	70	74
A249.0	T63	475	415	6	...	...	...	...
296.0	T7	270	140	5	80	205	60	70
308.0	F	195	110	2	70	150	90	...
319.0	F	235	130	3	85	165	...	74
	T6	275	185	3	95	...	...	74

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.7 (continued)

Alloy	Temper	Tension: Ultimate strength, MPa	Tension: Yield strength(a), MPa	Tension: Elongation in 5*D*, %	Hardness(b), HB 500 kg/10 mm	Shear ultimate strength, MPa	Fatigue endurance limit(b), MPa	Modulus of elasticity(c), GPa
Permanent mold casting (continued)								
324.0	F	205	110	4	70	...	...	...
	T5	250	180	3	90	...	...	...
	T62	310	270	3	105	...	...	...
332.0	T5	250	195	1	105	...	...	...
328.0	T6	235	145	1	65–95	...	...	...
333.0	F	235	130	2	90	185	105	...
	T5	235	170	1	100	185	85	...
	T6	290	205	2	105	230	105	...
	T7	255	195	2	90	195	85	...
336.0	T551	250	193	1	105	193	95	...
	T65	325	295	1	125	250	...	...
354.0	T61	360	270	6	...	...	...	...
	T62	380	310	3	...	...	...	...
355.0	F	185	105	4	...	...	...	70
	T51	205	165	2	75	165	...	70
	T6	290	185	4	90	235	70	70
	T61	310	275	2	105	250	70	70
	T7	275	205	2	85	205	70	70
	T71	250	215	3	85	185	70	70
C355.0	T6	330	195	8	90	...	...	70
	T61	315	235	6	100	...	...	70
	T62	330	255	5	100	...	...	70
356.0	F	180	125	5	...	...	...	73
	T51	185	140	2	...	...	...	73
	T6	260	185	5	80	205	90	73
	T7	220	165	6	70	170	75	73
	T71	170	...	3	60–90	...	...	73
A356.0	F	185	90	8	...	...	...	73
	T51	200	140	5	...	...	...	73
	T6	285	205	12	80	...	...	73
357.0	F	195	105	6	...	...	...	...
	T51	200	145	4	...	...	...	...
	T6	360	295	5	100	240	90	...
	T7	260	205	5	70	...	...	...
A357.0	T6	360	290	5	100	240	105	...
359.0	T61	330	255	6	...	...	...	...
	T62	345	290	5	...	...	110	...
A390.0	F	200	200	<1.0	110	...	...	...
	T5	200	200	<1.0	110	...	...	...
	T6	310	310	<1.0	145	...	115	...
	T7	260	260	<1.0	120	...	105	...
443.0	F	160	60	10	45	110	55	71
B443.0	F	145	40	6	30–60	...	...	...
A444.0	F	165	75	13	44	...	...	...
	T4	160	70	21	45	110	55	...
513.0	F	185	110	7	60	150	70	...
535.0	F	240	125	8	60–90	...	...	...
705.0	T5	255	115	10	55–75	...	...	...
707.0	T7	310	240	3	80–110	...	...	
711.0	T1	195	125	7	55–85	...	...	...
713.0	T5	220	150	4	60–90			
850.0	T5	160	75	12	45	105	60	71

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.7 (continued)

Alloy	Temper	Tension: Ultimate strength, MPa	Tension: Yield strength(a), MPa	Tension: Elongation in 5*D*, %	Hardness(b), HB 500 kg/10 mm	Shear ultimate strength, MPa	Fatigue endurance limit(b), MPa	Modulus of elasticity(c), GPa
Permanent mold casting (continued)								
851.0	T5	140	75	5	45	95	60	71
	T6	125	...	8	...	...	...	71
852.0	T5	220	160	5	70	145	75	71
Die casting								
360.0	F	305	170	3	75	195	140	71
A360.0	F	315	165	4	75	180	124	71
380.0	F	315	160	3	80	195	140	71
A380.0	F	325	160	4	80	185	140	71
383.0	F	310	150	4	75	...	145	71
384.0	F	330	165	3	85	200	140	...
390.0	F	280	240	<1	...	...	...	...
B390.0	F	315	250	<1	120	...	140	81
392.0	F	290	270	<1	...	...	...	...
413.0	F	295	145	3	80	170	130	71
A413.0	F	290	130	4	80	170	130	...
C443.0	F	230	95	9	65	200	115	71
518.0	F	310	193	5	80	200	140	...

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

defined by statistical analysis, and every technique permitted by practicality and specification was used to improve conformance. Alloying impurities were reduced, soluble phase components were adjusted, heat treatment practices stretched to permissible limits, and there was unusual concentration on the metallurgical structure of critical casting areas corresponding to test specimen locations.

Aluminum rocker arm requirements include strength at modestly elevated temperatures, hardness, and cost. Alloy 333.0, developed at the same time as 319.0 as the preferred secondary general-purpose permanent mold composition, was selected for this application. Over several years, randomly selected parts were destructively tested to ensure that casting quality and properties were maintained. The power of casting process and solidification conditions was evident. Typical mechanical properties for 333.0-T6 are 42 ksi (290 MPa) tensile strength, 30 ksi (210 MPa) yield strength, and 2% elongation. What was consistently demonstrated was 60 ksi (420 MPa) tensile strength, 50 ksi (350 MPa) yield strength, and 5% elongation, easily exceeding specification requirements for all conventional high-strength alloys in use at that time and matching many wrought compositions in plate and forged form with the advantage of near-net-shape and anisotropic properties. The application of premium engineered casting practices even to conventional casting alloys provides significant rewards.

The magnitude of the improvement achievable utilizing premium quality practices may be seen by comparing the values in Tables 8.9 and 8.10 with those in Tables 8.6 to 8.8, where differences of 5 to 15 ksi (35 to 105 MPa) or more in tensile yield strength and 3 to 4% in elongation are sometimes seen. Such differences are particularly significant when it is noted that the values for the premium quality castings are based on tests of specimens cut from the castings, whereas the published typical and minimum values for standard alloys are based on tests of separately cast tensile specimens.

Squeeze Casting. In recent years, broader use has been made of techniques for applying pressure to the metal while it is solidifying during the manufacture of castings. The most common and commercially most widely implemented technique is squeeze casting (see Chapter 3, Section 3.5.5).

The properties of representative castings produced by squeeze casting technology are presented in Table 8.11, as published in Ref 8 and 16, compared with the published typical properties of aluminum castings of the same alloys.

The strengths range from about the same as to about 5 ksi (35 MPa) above the typical properties for comparable sand and permanent mold castings, very significant considering that the values for the squeeze castings are based on tests of specimens cut from the castings themselves, whereas the typical values used in comparison are based on separately cast test bars. In addition, the elongations of the squeeze castings are, with only one exception, significantly higher than the published typical values.

In general, it appears that consistently better properties may be obtained by squeeze casting than by conventional casting technologies, in the absence of the application of premium casting technologies.

Table 8.8 Minimum mechanical properties of aluminum alloy sand, permanent mold, and die castings

Values are representative of separately cast test bars, not of specimens taken from commercial castings.

		Tension					Compression yield strength(a)		Shear ultimate strength		
		Ultimate strength		Yield strength(a)		Elongation in 2 in. or 4*D*,					
Alloy	Temper	ksi	MPa	ksi	MPa	%	ksi	MPa	ksi	MPa	Ref
Sand casting											
201.0	T7	60.0	415	50.0	345	3.0	51.0	350	36.0	250	6, 13(b)
204.0	T4	45.0	310	28.0	195	6.0	...	...	...	...	6
208.0	F	19.0	130	12.0	85	1.5	...	...	...	...	6
222.0	O	23.0	160	...	...	...	...	...	...	...	6
	T61	30.0	205	...	...	...	...	...	...	...	6
242.0	O	23.0	160	...	...	...	...	...	...	...	6
	T571	29.0	200	...	...	...	...	...	...	...	6
	T61	32.0	220	20.0	140	...	...	...	...	...	6
	T77	24.0	165	13.0	90	1.0	...	...	...	...	6
295.0	T4	29.0	200	13.0	90	6.0	...	...	...	...	6
	T6	32.0	220	20.0	140	3.0	...	...	...	...	6
	T62	36.0	250	28.0	195	...	...	...	...	...	6
	T7	29.0	200	16.0	110	3.0	...	...	...	...	6
319.0	F	23.0	160	13.0	90	1.5	...	...	...	...	6
	T5	25.0	170	...	...	...	...	...	...	...	6
	T6	31.0	215	20.0	140	1.5	...	...	...	...	6
328.0	F	25.0	170	14.0	95	1.0	...	...	...	...	6
	T6	34.0	235	21.0	145	1.0	...	...	...	...	6
354.0	T6	47.0	325	36.0	250	3.0	36.0	250	29.0	200	13(b)
355.0	T51	25.0	170	18.0	125	...	...	...	...	...	6
	T6	32.0	220	20.0	140	2.0	...	...	...	...	6
	T7	35.0	240	...	...	...	...	...	...	...	6
	T71	30.0	205	22.0	150	...	...	...	...	...	6
C355.0	T6	41.0	285	31.0	215	3.0	31.0	215	31.0	215	13(b)
	T6	36.0	250	25.0	170	2.5			...		6
356.0	F	19.0	130	...	...	2.0	...	...	...	...	6
	T51	23.0	160	16.0	110	...	...	...	...	...	6
	T6	22.0	150	15.0	105	0.7	15.0	105	15.0	105	13(b)
	T6	30.0	205	20.0	140	3.0	...	...	...	...	6
	T7	31.0	215	29.0	200	...	...	...	...	...	6
	T71	25.0	170	18.0	125	3.0	...	...	...	...	6
A356.0	T6	34.0	235	24.0	165	3.5			...		6
	T6	38.0	260	28.0	195	5.0	28.0	195	28.0	195	13(b)
357.0	T6	45.0	310	35.0	240	3.0	35.0	240	28.0	195	13(b)
359.0	T6	45.0	310	35.0	240	4.0	35.0	240	28.0	195	13(b)
443.0	F	17.0	115	7.0	50	3.0	...	...	...	...	6
B443.0	F	17.0	115	6.0	40	3.0	...	...	...	...	6
512.0	F	17.0	115	10.0	70	...	...	...	...	...	6
514.0	F	22.0	150	9.0	60	6.0	...	...	...	...	6
520.0	T4	42.0	290	22.0	150	12.0	...	...	...	...	
535.0	T	35.0	240	18.0	125	9.0	...	...	...	...	3
	T5	35.0	240	18.0	125	9.0	...	...	...	...	3
707.0	T5	33.0	230	22.0	150	2.0	...	...	...	...	3
	T7	37.0	255	30.0	205	1.0	...	...	...	...	3
710.0	F	32.0	220	20.0	140	2.0	...	...	...	...	3
	T5	32.0	220	20.0	140	2.0	...	...	...	...	3
712.0	F	34.0	235	25.0	170	4.0	...	...	...	...	3
	T5	34.0	235	25.0	170	4.0	...	...	...	...	3
713.0	F	32.0	220	22.0	150	3.0	...	...	...	...	3
	T5	32.0	220	22.0	150	3.0	...	...	...	...	3

(continued)

(a) For tensile compressive yield strengths, offset = 0.2%. (b) Values for class 1 only

Table 8.8 (continued)

		Tension					Compression yield strength(a)		Shear ultimate strength		
		Ultimate strength		Yield strength(a)		Elongation in 2 in. or 4*D*,					
Alloy	Temper	ksi	MPa	ksi	MPa	%	ksi	MPa	ksi	MPa	Ref
Sand casting (continued)											
771.0	T5	42.0	290	38.0	260	1.5	...	...	...	...	3
	T51	32.0	220	27.0	185	3.0	...	...	...	...	3
	T52	36.0	250	30.0	205	1.5	...	...	...	...	3
	T53	36.0	250	27.0	185	1.5	...	...	...	...	3
	T6	42.0	290	35.0	240	5.0	...	...	...	...	3
	T71	48.0	330	45.0	310	2.0	...	...	...	...	6
850.0	T5	16.0	110	...	...	5.0	...	...	...	...	6
851.0	T5	17.0	115	...	...	3.0	...	...	...	...	6
852.0	T5	24.0	165	18.0	125	...	...	...	...	...	6
Permanent mold casting											
201.0	T7	60.0	415	50.0	345	3.0	51.0	350	36.0	250	6
204.0	T4	48.0	330	29.0	200	8.0	...	...	...	...	6
208.0	T4	33.0	230	15.0	105	4.5	...	...	...	...	6
	T6	35.0	240	22.0	150	2.0	...	...	...	...	6
	T7	33.0	230	16.0	110	3.0	...	...	...	...	6
22.0	T551	30.0	205	...	...	...	...	...	...	...	6
	T65	40.0	275	...	...	...	...	...	...	...	6
242.0	T571	34.0	235	...	...	...	...	...	...	...	6
	T61	40.0	275	...	...	...	...	...	...	...	6
296.0	T7	35.0	240	...	...	2.0	...	...	...	...	6
308.0	F	24.0	165	...	...	2.0	...	...	...	...	6
319.0	F	28.0	195	14.0	95	1.5	...	...	...	...	6
	T6	34.0	235	...	...	2.0	...	...	...	...	6
332.0	T5	31.0	215	...	...	...	...	...	...	...	6
333.0	F	28.0	195	...	...	...	...	...	...	...	6
	T5	30.0	205	...	...	...	...	...	...	...	6
	T6	35.0	240	...	...	...	...	...	...	...	6
	T7	31.0	215	...	...	...	...	...	...	...	6
336.0	T551	31.0	215	...	...	...	...	...	...	...	6
	T65	40.0	275	...	...	...	...	...	...	...	6
354.0	T6	47.0	325	36.0	250	3.0	36.0	250	29.0	200	13(b)
	T61	48.0	330	37.0	255	3.0	...	...	...	...	6
	T62	52.0	360	42.0	290	2.0	...	...	...	...	6
355.0	T51	27.0	185	...	...	...	...	...	...	...	6
	T6	27.0	185	17.0	115.0	0.4	17.0	115	17.0	115	13(b)
	T6	37.0	255	...	...	...	...	...	...	...	6
	T62	42.0	290	...	...	...	...	...	...	...	6
	T7	36.0	250	...	...	...	...	...	...	...	6
	T71	34.0	235	27.0	185	...	...	...	...	...	6
C355.0	T6	41.0	285	31.0	215.0	3.0	31.0	215	31.0	215	13(b)
	T61	40.0	275	30.0	205	3.0	...	...	...	...	6
	T62										
356.0	F	21.0	145	...	...	...	...	...	...	...	6
	T51	25.0	170	...	...	...	...	...	...	...	6
	T6	25.0	170	16.0	110.0	0.7	16.0	110	16.0	110	13(b)
	T6	33.0	230	...	...	3.0	...	...	...	...	6
	T7	25.0	170	...	...	3.0	...	...	...	...	6
	T71	25.0	170	...	...	3.0	...	...	...	...	6
A356.0	F										
	T51										
	T6	38.0	260	28.0	195	5.0	28.0	195	28.0	195	13(b)
	T61	37.0	255	26.0	180	5.0	...	...	...	...	6
357.0	T6	45.0	310	35.0	240	3.0	35.0	240	28.0	195	6, 13(b)
A357.0	T61	45.0	310	36.0	250	3.0	...	...	...	...	6

(continued)

(a) For tensile compressive yield strengths, offset = 0.2%. (b) Values for class 1 only

Table 8.8 (continued)

		Tension					Compression yield strength(a)		Shear ultimate strength		
		Ultimate strength		Yield strength(a)		Elongation in 2 in. or 4*D*,					
Alloy	Temper	ksi	MPa	ksi	MPa	%	ksi	MPa	ksi	MPa	Ref
Permanent mold casting (continued)											
D357.0	T6	46.0	315	39.0	270	3.0	39.0	270	29.0	200	13(b)
359.0	T6	45.0	310	35.0	240	4	35.0	240	28.0	195	13(b)
	T61	45.0	310	34.0	235	4.0	...	...	...	...	6
	T62	47.0	325	38.0	260	3.0	...	...	...	...	6
443.0	F	21.0	145	7.0	50	2.0	...	...	...	...	6
B443.0	F	21.0	145	6.0	40	2.5	...	...	...	...	6
A444.0	T4	20.0	140	...	...	20.0	...	...	...	...	6
513.0	F	22.0	150	12.0	85	2.5	...	...	...	...	6
535.0	F	35.0	240	18.0	125	8.0	...	...	...	...	6
705.0	T5	37.0	255	17.0	120	10.0	...	...	...	...	6
707.0	T7	45.0	310	35.0	240	3.0	...	...	...	...	6
711.0	T1	28.0	195	18.0	125	7.0	...	...	...	...	6
713.0	T5	32.0	220	22.0	150	4.0	...	...	...	...	6
850.0	T5	18.0	125	...	...	8.0	...	...	...	...	6
851.0	T5	17.0	115	...	...	3.0	...	...	...	...	6
	T6	18.0	125	...	...	8.0	...	...	...	...	6
852.0	T5	27.0	185	...	...	3.0	...	...	...	...	6
Die casting											
360.0	F										
A360.0	F										
380.0	F										
A380.0	F										
383.0	F										
384.0	F										
390.0	F					Not available for die castings					
B390.0	F										
392.0	F										
413.0	F										
A413.0	F										
C443.0	F										
518.0	F										

(a) For tensile compressive yield strengths, offset = 0.2%. (b) Values for class 1 only

Semisolid casting also holds promise for providing higher-quality aluminum alloy castings, though it has as yet been less widely implemented successfully. The properties of some representative semisolid casting are presented in Table 8.12, again with published typical values for sand and permanent mold castings.

As for squeeze castings, the strengths of the semisolid castings range from about the same as to about 5 ksi (35 MPa) above the typical properties for comparable sand and permanent mold castings. Also, as in the case for squeeze castings, this is significant considering that the values for the semisolid castings are based on tests of specimens cut from the castings themselves, whereas the typical values used in comparison are based on separately cast test bars. The elongations of the semisolid castings are superior to the typical values for sand castings and are about the same as those for permanent mold castings.

It appears that with careful engineering of the process, some gains are possible with semisolid casting if the process can be successfully implemented on a broader scale.

High-Integrity Die Casting. The application of vacuum and other technologies to die casting has resulted in superior strengths and substantially higher elongations especially when combined with process features described in Chapter 3, Section 3.6.2. Figure

Table 8.9 Typical mechanical properties of premium engineered aluminum castings

Typical values of premium engineered casting are the same regardless of class or the area from which the specimen is cut; see Table 8.10 for minimum values.

		Tension					Fatigue endurance limit(a)	
		Ultimate strength		Yield strength		Elongation in 50 mm (2 in.),		
Alloy	Temper	ksi	MPa	ksi	MPa	%	ksi	MPa
A201.0	T7	72	495	65	448	6	14	97
A206.0	T7	65	445	59	405	6	13	90
224.0	T7	61	420	48	330	4	12.5	86
249.0	T7	68	470	59	407	6	11	75
354.0	T6	55	380	41	283	6	19.5(b)	135(b)
C355.0	T6	46	317	34	235	6	14	97
A356.0	T6	41	283	30	207	10	13	90
A357.0	T6	52	360	42	290	8	13	90

(a) Rotating beam reversed bending ($R = -1.0$) tests; endurance limit at 5×10^8 cycles. (b) Fatigue strength for 10^6 cycles. Source: Ref 8

8.2 (Ref 17) illustrates the properties obtained in European applications of this technology; specific heat treatment conditions were not cited but are assumed to comprise lower solution heat treatment temperature than that of the true T6 temper.

According to Altenpohl (Ref 17), the pressure in the casting chamber must be less than 50 millibars (5 kPa) to ensure the success of the vacuum casting technique, and by its application components previously made by other casting processes, forging, and impact extrusion have been replaced.

USCAR. In the period from 1999 to 2001, a number of automotive components were produced and evaluated by USCAR (Ref 18) to determine the statistical levels of strength achievable with several carefully controlled casting processes, including in some cases vacuum casting and squeeze casting. In all of the USCAR activity, the test results were based on specimens cut from specific locations in actual full-size castings. A summary of the tensile properties of the castings from that study are presented in Table 8.13.

While individual castings developed interesting properties in this study, none of the practices employed consistently provided properties above the ranges of typical and minimum values for comparable sand and permanent mold castings. The principal value of the study appears to have been that the published values based on cast test bars are pretty representative of what may be expected in closely controlled high-quality commercial production, provided consistent casting practices and quality control are exercised; in such cases, it appears that the use of the reduced strength guideline (75%) may not be necessary.

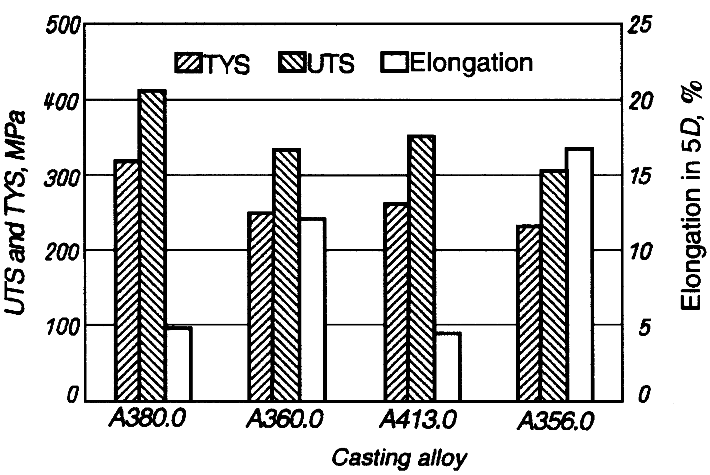

Fig. 8.2 Average tensile properties of representative aluminum alloy castings produced by vacuum technology. UTS, ultimate tensile strength; TYS, tensile yield strength. Source: Ref 17

8.4 Fatigue Properties of Aluminum Casting Alloys

Rotating beam reversed-bending fatigue data, at a stress ratio of –1.0, have long been a standard in aluminum industry publications, and extensive files of such data are available for aluminum casting alloys as presented herein. It is appropriate to recognize that such data are simply one of many indices of fatigue strength, and for specific applications, engineers may wish to consult data for other stress ratios such as 0.0, +0.1, and/or +0.5.

The fatigue properties of a rather wide range of sand and permanent mold castings (specimens per Appendix 3, Fig. A3.2) at room temperature are summarized in Table 8.14 (Ref 15).

Actual rotating beam ($R = -1.0$) fatigue curves for representative lots of castings at room temperature are shown in Data Set 6, in these cases often including both smooth and notched specimens of the types in Appendix 3, Fig. A3.2. In most cases, the specimens were as-cast test bars, tested with the as-cast surface in place; in a few cases, the tests were made with specimens machined from cast parts, such as pistons. A summary of the rotating-beam fatigue strengths from these tests of individual castings (as contrasted to the "typical" values in Table 8.14) is presented in Table 8.15. Most of these individual test results are compatible with the typical values in Table 8.14.

The fatigue strengths of a number of these alloys from similar tests at elevated temperatures are presented in Table 8.16.

A close review of the data in Tables 8.14 to 8.16 indicates to the authors that these data, though developed in accordance to good engineering laboratory standards, should be used very carefully, and the differences from alloy to alloy or among tempers of a

Table 8.10 Design (statistical minimum) mechanical properties of premium engineered aluminum alloy castings from MMPDS/MIL-HDBK-5 and AMS-A-21180

Values are for specimens taken from commercial castings.

Alloy	Temper	Type of casting	Location within casting	Strength class number	Tension: Ultimate strength, ksi	Tension: Ultimate strength, MPa	Tension: Yield strength, ksi	Tension: Yield strength, MPa	Tension: Elongation in 2 in. or 4D, %	Compression yield strength(a), ksi	Compression yield strength(a), MPa	Shear ultimate strength, ksi	Shear ultimate strength, MPa	Bearing: Ultimate strength(b), e/D = 1.5, ksi	Bearing: Ultimate strength(b), e/D = 1.5, MPa	Bearing: Ultimate strength(b), e/D = 2.0, ksi	Bearing: Ultimate strength(b), e/D = 2.0, MPa	Bearing: Yield strength(b), e/D = 1.5, ksi	Bearing: Yield strength(b), e/D = 1.5, MPa	Bearing: Yield strength(b), e/D = 2.0, ksi	Bearing: Yield strength(b), e/D = 2.0, MPa
A201	T7	Unspecified	Designated	1	60	414	50	345	3	51	352	36	250	95	655	122	841	74	510	87	600
				2	60	414	50	345	5	51	352	36	250	95	655	122	841	74	510	87	600
			Undesignated	10	60	414	50	345	3	51	352	36	250	95	655	122	841	74	510	87	600
				11	56	386	48	331	1.5	49	338	34	234	88	607	114	786	71	490	83	572
354.0	T6	Unspecified	Designated	1	47	324	36	248	3	36	248	29	200	81	559	101	697	57	393	67	462
				2	50	345	42	290	2	42	290	31	214	86	593	107	738	66	455	78	538
			Undesignated	10	47	324	36	248	3	36	248	29	200	81	559	101	697	57	393	67	462
				11	43	297	33	228	2	33	228	27	186	74	510	92	635	52	359	62	428
355.0	T6	PM	As specified	N/A	27	186	17	117	0.33	17		17	117	46	317	58	400	27	186	32	221
C355.0	T6	Unspecified	Designated	1	41	283	31	214	3	31	214	26	179	70	483	88	607	49	338	58	400
				2	44	303	33	228	3	33	228	28	193	75	517	94	648	52	359	62	428
				3	50	345	40	276	2	40	276	31	214	86	593	107	738	63	435	75	517
			Undesignated	10	41	283	31	214	3	31	214	26	179	70	483	88	607	49	338	58	400
				11	37	255	30	207	1	30	207	23	159	63	435	79	545	47	324	55	379
				12	35	241	28	193	1	28	193	22	152	60	414	75	517	44	303	52	359
356.0	T6	Sand	All	N/A	22	152	15	103	0.7	15	103	14	97	38	262	47	324	24	166	28	193
		IM	As specified	N/A	25	172	16	110	1	16	110	16	110	43	297	53	366	25	172	30	207
		PM	As specified	N/A	25	172	16	110	0.7	16	110	16	110	43	297	53	366	25	172	30	207
A356.0	T6	Unspecified	Designated	1	38	262	28	193	5	28	193	24	166	65	448	81	559	44	303	52	359
				2	40	276	30	207	3	30	207	25	172	69	476	86	593	47	324	56	386
				3	45	310	34	234	3	34	234	28	193	77	531	96	662	55	379	63	435
			Undesignated	10	38	262	28	193	5	28	193	24	166	65	448	81	559	44	303	52	359
				11	33	228	27	186	3	27	186	21	145	57	393	71	490	43	297	50	345
				12	32	221	22	152	2	22	152	20	138	55	379	68	469	35	241	41	283
	T6P	All	All	N/A	32	221	22	152	0.33	22	152	20	138	55	379	68	469	35	241	41	283
A357.0	T6	All	Designated	1	45	310	35	241	3	35	241	28	193	77	531	96	662	55	379	65	448
				2	50	345	40	276	5	40	276	31	214	86	593	107	738	63	435	75	517
			Undesignated	10	38	262	28	193	5	28	193	24	166	65	448	81	559	44	303	52	359
				11	41	283	31	214	3	31	214	26	179	70	483	88	607	49	338	58	400
				12	45	310	35	241	3	35	241	28	193	77	531	96	662	55	379	65	448
D357.0	T6	Unspecified	Designated	N/A	46	317	39	269	3	39	269	29	200	79	545	99	683	62	428	73	503
			(<2.501 in.)	N/A	49	338	41	283	. . .	41	283	31	214	84	579	105	724	65	448	77	531
			Undesignated	N/A	45	310	36	248	2	36	248	28	193	77	531	96	662	57	393	67	462
359.0	T6	All	Designated	1	45	310	35	241	4	35	241	28	193	77	531	96	662	55	379	65	448
				2	47	324	38	262	3	38	262	29	200	81	559	101	697	60	414	71	490
			Undesignated	10	45	310	34	234	4	34	234	28	193	77	531	96	662	54	372	63	435
				11	40	276	30	207	3	30	207	25	172	69	476	86	593	47	324	56	386

Metric units are as calculated directly, not rounded per industry practice for guaranteed minimum values. (a) For tensile and compressive yield strengths, offset = 0.2%. (b) e/D equals edge distance, e, divided by bearing pin diameter, D. Source: Ref 15; tensile minimum values are from AMS-A-21180 (previously MIL-A-21180).

Table 8.11 Tensile properties of representative squeeze-cast aluminum alloy castings

Values are averages for an unspecified number of tests of specimens taken from commercial castings.

			Ultimate strength		Yield strength(a)			
Alloy	Temper	Casting process	ksi	MPa	ksi	MPa	Elongation in 2 in. or 4*D*, %	Ref
A206	T4	Squeeze (1)	59.5	410	37.5	258	23.5	16
		Squeeze (2)	56.5	390	34.2	236	24.0	8
	T4	Typical, sand cast	55	379	36	248	6.0	4
	T4	Typical, permanent mold	62	428	38	262	17.0	4
356.0	T6	Squeeze cast	44.8	309	38.5	265	3.0	8
	T6	Squeeze cast (quenched)	46.0	371	33.6	232	11.9	16
	T6	Typical, sand cast	33	228	24	166	3.5	4
	T6	Typical, permanent mold	38	262	27	186	5.0	4
	T61	Squeeze cast	46.0	371	33.6	232	11.9	8
A356.0	T4	Squeeze cast	38.4	265	25.9	179	20.0	8
	T61	Squeeze cast	43.5	300	35.8	247	6.6	16
	T61	Typical, permanent mold	41.0	283	30.0	207	10.0	4
B356.0	T61	Squeeze cast	43.9	303	32.3	223	17.6	16
357.0	T6	Squeeze cast	48.0	331	36.5	252	9.0	16
	T6	Typical, sand cast	50	345	43	297	2.0	4
	T6	Typical, permanent mold	52	359	43	297	5.0	4
535.0	F	Squeeze cast	45.2	312	22.1	152	34.2	8
	F	Typical, permanent mold	40	280	20	140	13.0	4

(a) For tensile yield strengths, offset = 0.2%.

given alloy should not necessarily be considered to consistently represent their performance in finished castings. The primary reason for this is the fact that many of the data are for cast test bars that were cast to finished specimen size, or with only polishing of the surface, and there is evidence that there are favorable residual stresses in the as-cast surface that may have misleadingly positive influence on the fatigue life and strength. Consider, for example, the data for one lot of 380.0-F cast test bars for which tests were made with as-die cast test bars and with 0.01 in. and 0.025 in. removed, shown in Data Set 6. The endurance limits for specimens with the surface machined were lower, with the difference increasing with the greater amount of the surface machined, that is:

	Endurance limit	
Surface finish of fatigue specimen	ksi	MPa
As cast	21.0	145
0.01 in. (0.25 mm) removed	19.5	134
0.025 in. (0.64 mm) removed	17.5	121

Table 8.12 Tensile properties of representative semisolid cast aluminum alloy castings

Values are averages for an unspecified number of tests of specimens taken from commercial castings.

			Ultimate strength		Yield strength(a)			
Alloy	Temper	Casting process	ksi	MPa	ksi	MPa	Elongation in 2 in. or 4*D*, %	Ref
206.0	T7	Semisolid cast	56.0	317	46.0	317	6.0	8
	T4	Typical, sand cast	50	345	28	193	10.0	4
	T7	Typical, permanent mold	63	435	50	345	11.7	4
356.0	T5	Semisolid cast	34.0	234	25.0	172	11.0	8
	T51	Typical, sand cast	25	172	20	138	2.0	4
	T6	Semisolid cast	43.0	296	28.0	193	12.0	8
	T6	Typical, sand cast	33	228	24	164	3.5	4
A356.0	T6	Typical, semisolid	55	380	33	225	12.0	16
		Typical, permanent mold	41	280	30	205	10.0	16
357.0	T5	Semisolid cast	43.0	296	30.0	207	11.0	8
	T51	Typical, sand cast	26	179	17	117	3.0	4
	T6	Semisolid cast	52.0	358	42.0	290	10.0	8
	T6	Typical, sand cast	50	345	43	296	2.0	4
A357.0	T61	Semisolid cast	45.9	316	35.3	243	8.4	16
	T62	Semisolid cast	43.5	300	35.3	243	6.6	16
	T6	Typical, sand cast	46	317	36	248	3.0	4
	T6	Typical, permanent mold	50	345	40	276	10.0	4

(a) For tensile yield strengths, offset = 0.2%.

Table 8.13 Average and three-sigma minimum tensile properties of aluminum alloy castings from USCAR program

Values are for specimens taken from commercial castings.

				Average						Three-sigma minimum					
				Ultimate strength		Yield strength(a)		Elongation in 2 in. or 4D,	Reduction of area,	Ultimate strength		Yield strength		Elongation in 2 in. or 4D,	Reduction of area,
Alloy	Temper	Type of casting	Vehicle component	ksi	MPa	ksi	MPa	%	%	ksi	MPa	ksi	MPa	%	%
A356.0	T6	Tilt mold pour(b)	Rear knuckle	47.6	328	36.5	252	12.3	16.7	45.5	314	33.3	230	5.2	8.1
		Tilt mold pour(b)	Front cradle	41.8	288	32.1	221	7.1	9.3	38.7	267	29.8	206	2.1	2.5
		Tilt mold pour(b)	Low control arm	43.5	300	29.7	205	12.0	13.3	39.6	273	27.5	190	3.6	4.7
		Lost foam	Transfer case	37.3	257	29.1	201	6.0	11.8	28.5	197	25.7	177	0.0	5.6
		VRC/PRC	Front knuckle	44.8	309	33.9	234	10.7	15.6	43.0	297	32.6	225	6.5	6.7
		Squeeze cast	Front knuckle	41.4	286	31.6	218	9.5	14.9	37.9	261	29.3	202	1.8	0.0
	Published typical and minimum			40.0	275	30.0	205	6.0	...	38.0		28.0		5.0	...
A357.0	T6	Semisolid	Low control arm	48.8	337	40.5	279	8.6	10.5	45.6	315	37.8	261	4.3	5.3
	Published typical and minimum			52.0		43.0		5.0		45.0	310	36.0	250	3.0	...
365.0	T6	AV die cast	Body casting	29.6	160	20.0	138	19	...	28.0	193	18.4	127	14.0	...
A380.0	F	HP die cast	Trans. case	27.1	187	25.5	176	...	...	5.5	38	21.0	145	...	...
	Published typical			47.0	345	23.0	295	4.0		...	...	...	...	...	...

(a) For tensile yield strengths, offset = 0.2%. (b) Tilt mold pour process is a variation of permanent mold casting. Source: Ref 18

Table 8.14 Typical rotating-beam fatigue strengths of aluminum alloy castings at room temperature

Fatigue strengths determined from reversed-bending tests of 0.330 in. diam specimens in R.R. Moore rotating beam machines

		Fatigue strength at life of										Endurance limit at 5 × 10^8 cycles	
		10^4 cycles		10^5 cycles		10^6 cycles		10^7 cycles		10^8 cycles			
Alloy	Temper	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
Sand casting													
204.0	T4	...	...	...	...	...	...	...	...	...	...	11.0	76
A206.0	T71	...	...	...	...	...	...	...	...	...	...	23.0	159
208.0	F	...	...	...	...	...	...	...	...	...	...	11.0	76
222.0	T2	...	...	14.5	100	12.0	83	10.5	72	10.0	69	9.5	66
224.0	T7	...	...	27.0	186	16.5	114	12.5	86	12.0	83	12.0	83
A240.0	F	...	...	29.0	200	23.0	159	19.0	131	18.0	124	17.5	121
242.0	O	...	...	...	...	...	...	...	...	...	...	8.0	55
	T77	...	...	19.0	131	14.0	97	11.5	79	10.5	72	10.5	72
	T571	...	...	...	...	...	...	...	...	...	...	11.0	76
249.0	T7	47.0	324	26.0	179	14.5	100	11.5	79	11.0	76	11.0	76
295.0	T4	...	...	...	...	...	...	...	...	...	...	7.0	48
	T6	...	...	...	...	...	...	...	...	...	...	7.5	52
	T62	...	...	...	...	...	...	...	...	...	...	8.0	55
308.0	F	...	...	...	...	...	...	...	...	...	...	11.0	76
319.0	F	...	...	...	...	...	...	...	...	...	...	10.0	69
	T5	...	...	...	...	...	...	...	...	...	...	11.0	76
	T6	...	...	...	...	...	...	...	...	...	...	11.0	76
355.0	T51	...	...	...	...	...	...	...	...	...	...	8.0	55
	T6	...	...	...	...	...	...	...	...	...	...	9.0	62
	T61	...	...	...	...	...	...	...	...	...	...	10.0	69
	T7	...	...	...	...	...	...	...	...	...	...	10.0	69
	T71	...	...	21.0	145	15.0	103	12.0	83	11.0	76	10.5	72
	T77	...	...	...	...	...	...	...	...	...	...	10.0	69
A355.0	T51	...	...	15.5	107	11.0	76	9.5	66	8.5	59	8.0	55
C355.0	T6	...	...	28.0	193	19.0	131	16.0	110	14.5	100	14.0	97
356.0	T51	...	...	...	...	...	...	...	...	...	...	8.0	55
	T6	33.0	228	24.5	169	18.0	124	14.5	100	12.5	86	12.0	83
	T7			21.0	145	14.5	100	10.5	72	9.5	66	9.5	66
	T71	...	...	...	...	...	...	...	...	...	...	8.5	59
357.0	T6	...	...	...	...	...	...	...	...	...	...	9.0	62
A390.0	F, T5	...	...	...	...	...	...	...	...	...	...	10.0	69
	T6	...	...	...	...	...	...	...	...	...	...	13.0	90
443.0	F	...	...	...	...	...	...	...	...	...	...	8.0	55
511.0	F	...	...	...	...	...	...	...	...	...	...	8.0	55
514.0	F	...	...	...	...	...	...	...	...	...	...	7.0	48
518.0	F	28.0	193	20.0	138	13.5	93	10.5	72	9.5	66	9.0	62
535.0	F	...	...	...	...	...	...	...	...	...	...	10.0	69
B535.0	F	...	...	...	...	...	...	...	...	...	...	9.0	62
520.0	T4	...	...	...	...	...	...	...	...	...	...	8.0	55
710.0	F, T5	...	...	...	...	...	...	...	...	...	...	8.0	55
713.0	F, T5	...	...	...	...	...	...	...	...	...	...	9.0	62
850.0	T5	...	...	...	...	...	...	...	...	...	...	8.0	55
852.0	T5	...	...	...	...	...	...	...	...	...	...	10.0	69
Permanent mold casting													
242.0	T571	34.0	234	26.0	179	20.0	138	16.5	114	15.5	107	15.0	103
	T61	...	...	...	...	...	...	...	...	...	...	9.5	66
296.0	T6	...	...	...	...	...	...	...	...	...	...	10.0	69
308.0	F	...	...	...	...	...	...	...	...	...	...	13.0	90
319.0	F	...	...	...	...	...	...	...	...	...	...	12.0	83
	T6	...	...	...	...	...	...	...	...	...	...	12.0	83
333.0	F	...	...	...	...	...	...	...	...	...	...	14.0	97
	T5	...	...	22.5	155	18.0	124	15.5	107	14.5	100	13.5	93
	T6	...	...	...	...	...	...	...	...	...	...	15.0	103
	T7	...	...	24.0	166	18.5	128	15.5	107	13.5	93	12.5	86
336.0	T551	...	...	21.0	145	18.0	124	16.0	110	14.5	100	13.5	93
354.0	T6	50.0	345	40.0	276	31.0	214	25.5	176	21.0	145	19.5	134
	T62	...	...	...	...	...	...	...	...	...	...	17.0	117
355.0	T6	...	...	...	...	...	...	...	...	...	...	10.0	69
	T62	...	...	36.0	248	29.0	200	23.0	159	18.0	124	15.5	107
	T71	...	...	27.0	186	21.0	145	17.0	117	14.5	100	13.0	90
C355.0	T61	...	...	...	...	...	...	...	...	...	...	14.0	97
356.0	T6	39.0	269	31.0	214	24.5	169	19.5	134	15.0	103	13.0	90
	T7	...	...	...	...	...	...	...	...	...	...	11.0	76
A356.0	T6	...	...	29.0	200	23.0	159	17.0	117	14.0	97	13.0	90
	T61	...	...	...	...	...	...	...	...	...	...	13.0	90
357.0	T6	...	...	...	...	...	...	...	...	...	...	13.0	90
A357.0	T61	...	...	...	...	...	...	...	...	...	...	15.0	103

(continued)

Metric values of strength determined by multiplying strengths originally determined in English units by conversion factor of 6.897. English units measured to nearest 0.5 ksi; metric units rounded to nearest MPa. Source: Aluminum Association and Alcoa publications

Table 8.14 (continued)

		Fatigue strength at life of										Endurance limit at 5 × 10^8 cycles	
		10^4 cycles		10^5 cycles		10^6 cycles		10^7 cycles		10^8 cycles			
Alloy	Temper	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
Permanent mold casting (continued)													
359.0	T61	43.0	297	34.0	234	27.0	186	21.5	148	17.5	121	16.5	114
	T62	...	...	37.0	255	28.0	193	21.0	145	17.0	117	16.0	110
A390.0	T6	...	...	...	...	...	...	...	...	...	...	17.0	117
	T7	...	...	...	...	...	...	...	...	...	...	15.0	103
B443.0	F	...	...	...	...	...	...	...	...	...	...	8.0	55
513.0	F	...	...	...	...	...	...	...	...	...	...	10.0	69
711.0	F	...	...	...	...	...	...	...	...	...	...	11.0	76
713.0	T5	...	...	...	...	...	...	...	...	...	...	9.0	62
850.0	T5	...	...	...	...	...	...	...	...	...	...	9.0	62
851.0	T5	...	...	...	...	...	...	...	...	...	...	9.0	62
852.0	T5											11.0	76
Die casting													
360.0	F	...	...	30.0	207	25.0	172	23.0	159	21.0	145	19.0	131
A360.0	F	...	...	...	...	...	...	...	...	...	...	18.0	124
364.0	F	...	...	...	...	...	...	...	...	...	...	18.0	124
380.0	F	...	...	28.0	193	22.0	152	20.5	141	20.0	138	20.0	138
A380.0	F	...	...	...	...	...	...	...	...	...	...	20.0	138
384.0	F	39.0	269	32.0	221	26.0	179	23.5	162	22.0	152	21.5	148
390.0	F	...	...	...	...	...	...	...	...	...	...	11.0	76
B390.0	F	...	...	...	...	...	...	...	...	...	...	20.0	138
413.0	F	...	...	...	...	...	...	...	...	...	...	19.0	131
A413.0	F	...	...	...	...	...	...	...	...	...	...	19.0	131
C443.0	F	...	...	...	...	...	...	...	...	...	...	16.0	110
513.0	F	...	...	...	...	...	...	...	...	...	...	18.0	124
515.0	F	...	...	...	...	...	...	...	...	...	...	19.0	131
518.0	F	...	...	...	...	...	...	...	...	...	...	20.0	138

Metric values of strength determined by multiplying strengths originally determined in English units by conversion facator of 6.897.
English units measured by nearest 0.5 ksi; metric units rounded to nearest MPa. Source: Aluminum Association and Alcoa publications

Other illustrations of such differences are found in Data Set 6, in which the fatigue results for permanent mold cast 242.0-T571 and for sand cast 355.0-T7 and -T71, for which tests were made of both as-cast test bars and of specimens taken from actual castings. In both cases, as illustrated in the table that follows, the fatigue endurance limits were significantly lower for specimens machined from the castings than for the as-cast test bars:

		Endurance limit	
Alloy and temper	Fatigue specimens	ksi	MPa
242.0-T571	As-cast test bars	15.0	103
	Machined from cast pistons	9.5	66
C355.0-T7, -T71	As-cast test bars	10.5	72
	Machined from cast crankcase	5.5	38

In these cases, it should be noted that the as-cast test bars and the cast parts used for each alloy were totally different lots, and so the comparisons are not perfect; however, the differences seem to support indications that there is a positive influence on fatigue life of having cast-to-shape fatigue specimens.

This, of course, also may suggest that for cast parts where the surfaces are in highly stressed regions, the design of the casting may favor having the as-cast surface intact, with the resultant positive residual stresses working in favor of improved performance. In any such considerations, care should be taken to provide for a smooth, stress-raiser-free finished surface on the as-cast part.

Ignoring such influences, for the moment, of the alloys and tempers for which data are available, those exhibiting the highest fatigue strengths include sand cast A206.0-T71 and A240.0-F, permanent mold cast 354.0-T6, 359.0-T6, and A390.0-T6. Among the die cast alloys, there was less overall variability, but 384.0-F exhibited the highest strengths. The role of positive residual stress patterns in promoting these specific alloys is unknown, but it might be noted that all of the specimens for the die castings had as-cast surfaces, perhaps accounting for their apparently overall higher fatigue strengths. Overall, it is fair to say that with a few exceptions there is not a great amount of variability in endurance limits among the alloys, for either smooth or notched specimens.

At elevated temperatures, as at room temperature, there are not very great differences among the endurance limits of the various alloys.

It should be emphasized that all of the values in Tables 8.14 and Table 8.16 are based on tests of small specimens machined from castings, including in many (regrettably unidentified) cases, cast test bars. These values may not be representative of the performance of specific cast components. More detail on the variations that may be observed is illustrated in the following sections.

8.4.1 Influence of Casting Quality on Fatigue Strength

Several studies have been reported indicating the influence of casting process and microstructure on fatigue strength.

Data from Juvinall (Ref 20), reproduced in Fig. 8.3, illustrate that in general the fatigue strengths of aluminum castings are not as high as those of wrought aluminum products (i.e., components made from plate, forgings, or extrusions). Further, indications from this

Table 8.15 Summary of reversed-bending fatigue curves for representative lots of aluminum alloy castings

Stress ratio, $R = -1.0$

						Endurance limit(c), ksi			
				Type of specimens(b)		Smooth		Notched	
Alloy	Temper	Cast part(a)	Lot ID	Smooth	Notched	ksi	MPa	ksi	MPa
Plaster mold casting									
255.0	T62	CTB	D1699	X	X	15.0	103	7.5	52
C355.0	T62	CTB	D1701	X	X	15.0	103	7.5	52
356.0	T6	CTB	D223A,B	X	X	12.0	83	8.0	55
	T61	CTB	D1702	X	X	13.0	90	7.5	52
A356.0	T61	CTB	D1703	X	X	12.0	83	7.0	48
	T61	Casting	206548	X	X	8.0	55	8.0	55
	T61 PEC	Casting	206547	X	X	11.0	76	7.5	52
	T62	Casting	175138	X	...	13.0	90	...	...
Sand casting									
213.0	F	CTB	C6611	X	X	10.0	69	7.5	52
224.0	T62	CTB	E8419C	X	X	12.5	86	7.5	52
240.0	F	CTB	D23,D403	X	...	18.0	124	...	...
		CTB	D424	X	...	13.0	90	...	...
	F	CTB	D2551	X	X	17.0	117	7.5	52
242.0	O(T21)	CTB	C7043F	X	X	10.0	69	8.0	55
	T571	CTB	C7043A	X	X	12.0	83	9.0	62
	T75	CTB	L2567	X	X	9.0	62	5.5	38
	T77	CTB	C5107	X	X	11.5	79	7.5	52
		CTB	L2579	X	...	9.5	66	...	...
		CTB	C6765B	X	X	10.0	69	7.0	48
249.0	T63	CTB	E8083D,E8115	X	X	9.5	66	6.0	41
295.0	T6	CTB	C3508	X	...	7.0	48	...	...
		CTB	Unknown	X	...	7.5	52	...	...
		CTB	L1585	X	...	7.0	48	...	...
	T62	CTB	Unknown	X	...	7.0	48	...	...
		CTB	L1670	...	X	...	...	5.0	34
308.0	F	CTB	117105	X	X	11.5	79	7.0	48
319.0	F	CTB	C6884E	X	X	12.0	83	9.0	62
	T5	CTB	C6884T	X	X	11.0	76	8.0	55
	T6	CTB	C6884K	X	X	12.5	86	10.0	69
	T71	CTB	C6884L	X	X	10.5	72	8.0	55
355.0	T51	CTB	C6285M	X	X	10.0	69	6.0	41
	T6	CTB	5 lots	X	...	10.0	69	...	...
		CTB	5 lots	...	X	...	...	9.0	62
	T61	CTB	C3509-T61	X	X	9.5	66	7.5	52
	T7	CTB	C6285K	X	X	10.5	72	7.0	48
	T71	CTB	C6285L	X	X	11.5	79	7.5	52
	T7,T71	CTB	Unknown	X	X	10.5	72	7.0	48
		Cast crankcase	175472	X	...	5.5	38	...	...
A355.0	T51	CTB	L758	X	...	8.5	59	...	...
	T59	CTB	L759	X	...	8.5	59	...	...
	T6	CTB	P255A	X	...	7.5	52	...	...
B355.0	T6	CTB	L3032	X	...	8.5	59	...	...
		CTB	L3032	...	X	...	...	8.5	59
356.0	T51	CTB	C6385D	X	X	9.0	62	6.5	45
		CTB	L757	X	...	6.5	45	...	...
		CTB	L1661	...	X	...	...	6.0	41
	T6	CTB	L1704	X	...	7.5	52	...	...
		CTB	C6385K	X	X	12.0	83	9.0	62
		CTB	C3510	X	...	8.5	59	...	...
		CTB	C3510	...	X	...	...	6.0	41
	T7,T71	CTB	C3510,C6385L	X	...	8.0	55	...	...
		CTB	C3510,C6385L	...	X	...	...	7.0	48
B443	F	CTB	117104	X	X	8.5	59	6.0	41
712.0	F	CTB	C8455	X	X	9.5	66	7.0	48
A712.0	F	CTB	C8533	X	X	10.5	72	7.0	48
		CTB	C9004H	X	X	7.5	52	6.0	41
852.0	T5	CTB	C8454	X	X	9.5	66	6.0	41
Permanent mold casting									
213.0	F	CTB	D665	X	X	17.0	117	7.5	52
		CTB	L1652	X	X	9.5	66	7.0	48
242.0	T571	CTB	C6156	X	X	15.0	103	7.5	52
		CTB	C9609D	X	X	15.5	107	9.0	62
		Pistons	301974	X	...	9.5	66	...	...
		VRC pistons	317189	X	...	10.0	69	...	...
	T61	CTB	C6156	X	X	15.0	103	7.5	52

(continued)

(a) CTB, cast test bars; casting, undefined cast part other than CTB; specific part given if stated on data sheet. (b) Specimens shown in Appendix 3, Fig. A3.2(b) for notched specimen, notch-tip radius ≤ 0.001 in; $K_t \geq 12$. (c) Endurance limit at 500 million cycles. Source: Ref 19

Table 8.15 (continued)

Alloy	Temper	Cast part(a)	Lot ID	Type of specimens(b) Smooth	Type of specimens(b) Notched	Endurance limit(c), ksi Smooth ksi	Endurance limit(c), ksi Smooth MPa	Endurance limit(c), ksi Notched ksi	Endurance limit(c), ksi Notched MPa
Permanent mold casting (continued)									
296.0	T6	CTB	C5449	X	X	12.0	83	8.5	59
	T7	CTB	C5449	X	X	8.0	55	6.5	45
308.0	F	CTB	C8902	X	X	13.0	90	8.0	55
332.0	T5	CTB	C8281	X	X	14.0	97	8.0	55
333.0	F	CTB	C6028	X	X	13.0	90	8.0	55
	T5	CTB	C6028	X	X	12.0	83	8.0	55
			D278B	X	X	13.0	90	7.5	52
	T6	CTB	C6028	X	X	15.0	103	10.0	69
	T7	CTB	C6028	X	X	12.0	83	9.0	62
			C9176C	X	X	12.0	83	8.0	55
336.0	T551	CTB	105678	X	X	13.5	93	7.5	52
A344.0	T4	CTB	317644	X	X	9.0	62	3.5	24
354.0	T61	CTB	D3860	X	X	19.0	131	12.0	83
			E6161	X	X	15.0	103	9.0	62
355.0	T51	CTB	C8067K	X	X	12.5	86	7.0	48
	T6	CTB	C5448	X	X	10.0	69	8.0	55
			C8067K	X	X	16.0	110	10.5	72
	T62	CTB	C5448	X	X	9.5	66	6.0	41
			C8067K	X	X	15.5	107	7.5	52
	T7	CTB	C8067K	X	X	13.0	90	8.5	59
	T71	CTB	C5448	X	X	9.5	66	6.0	41
			C8067K	X	X	12.5	86	8.0	55
C355.0	T61	CTB	D2245B	X	X	12.5	86	10.0	69
	T61 PEC	PE casting	206428	X	X	12.0	83	9.0	62
356.0	T6	CTB	C6235	X	X	13.0	90	7.5	52
	T7	CTB	C6235	X	X	10.5	72	5.0	34
A356.0	T6	CTB	D2543	X	X	13.5	93	7.5	52
	T61	Casting	206587	X	X	8.0	55	7.5	52
		PE casting	206588	X	X	8.0	55	7.5	52
		PE casting	206547	X	X	ND	...	ND	...
A357.0	T61	CTB	302022	X	X	12.5	86	7.5	52
			302023	X	X	13.5	93	7.0	48
	T62	Casting	302108	X	X	11.0est	76est	6.0	41
359.0	T61	CTB	D4228	X	X	16.0	110	11.0	76
	T62	CTB	E2520A	X	X	15.0	103	9.0	62
B443.0	F	CTB	118348	X	X	7.0	48	4.0	28
C712.0	F	CTB	C8278	X	X	11.0	76	6.5	45
850.0	F	CTB	R8036	X	...	9.0	62	...	...
	T101	CTB	270257	X	...	10.0	69	...	...
	T5	CTB	270263	X	...	8.5	59	...	...
851.0	T6	CTB	C1670	X	...	8.5	59	...	...
852.0	T5	CTB	D3278	X	X	11.5	79	5.0	34
			C8094	X	X	10.5	72	5.0	34
Die casting									
360.0	F	CTB	P1003	X	...	19.0	131	...	...
A360.0	F	CTB	P1004	X	...	18.0	124	...	...
364.0	F	CTB	206520	X	...	15.0	103	...	...
380.0	F	CTB	P1005	X	...	18.5	128	...	...
		CTB-as cast	147979	X	...	21.0	145	...	...
		0.01 in. removed		X	...	19.5	134	...	...
		0.025 in. removed		X	...	17.5	121	...	...
		Notches		...	X	...	...	7.0	48
A380.0	F	CTB	P1006	X	...	21.5	148	...	...
383.0	F	CTB	P1007	X	...	21.0	145	...	...
390.0	F	CTB-as cast	317782	X	X	19.0	131	10.5	72
		CTB machined	317782	X	X	19.0	131	10.5	72
413.0	F		P998	X	...	19.0	131	...	...
			317250	X	X	13.0	90	5.5	38
B443.0	F	CTB	P1000	X	...	16.5	114	...	...
518.0	F	CTB	158837	X	X	15.5	107	6.0	41
			P1002	X	...	22.5	155	...	...

(a) CTB, cast test bars; casting, undefined cast part other than CTB; specific part given if stated on data sheet. (b) Specimens shown in Appendix 3, Fig. A3.2(b) for notched specimen, notch-tip radius ≤ 0.001 in; $K_t \geq 12$. (c) Endurance limit at 500 million cycles. Source: Ref 19

Table 8.16 Typical rotating-beam fatigue strength of aluminum casting alloys at elevated temperatures

Fatigue strengths determined from reversed-bending tests of 0.330 in. diam specimens in R.R. Moore or cantilever-beam rotating-beam machines

		Test temperature		Fatigue strength at life of										Endurance limit at 5×10^8 cycles	
				10^4 cycles		10^5 cycles		10^6 cycles		10^7 cycles		10^8 cycles			
Alloy	Temper	°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
Sand casting															
222.0	T2	RT	RT	...	...	14.5	100	12.0	83	10.5	72	10.0	69	9.5	66
		300	150	...	...	13.0	90	11.0	76	9.5	66	9.0	62	8.0	55
		400	205	...	...	11.5	79	9.5	66	7.5	52	6.0	41	5.0	34
		500	260	...	...	10.0	69	8.0	55	6.0	41	5.0	34	4.0	28
224.0	T7	RT	RT	...	...	27.0	186	16.5	114	12.5	86	12.0	83	12.0	83
		400	205	...	...	22.0	152	13.5	93	8.5	59	7.0	48	7.0	48
		500	260	...	...	19.5	134	11.5	79	7.0	48	6.0	41	6.0	41
A240.0	F	RT	RT	...	...	29.0	200	23.0	159	19.0	131	18.0	124	17.5	121
		300	150	...	...	19.0	131	14.5	100	13.0	90	12.5	86	12.5	86
		400	205	...	...	17.5	121	13.0	90	11.0	76	10.5	72	10.5	72
		500	260	...	...	16.0	110	11.5	79	9.0	62	8.5	59	8.5	59
		600	315	...	...	14.0	97	9.5	66	7.0	48	5.5	38	5.0	34
242.0	T77	RT	RT	...	...	19.0	131	14.0	97	11.5	79	10.5	72	10.5	72
		300	150	...	...	15.0	103	10.5	72	8.0	55	7.5	52	7.5	52
		400	205	...	...	14.0	97	10.0	69	7.5	52	6.5	45	6.5	45
		500	260	...	...	12.5	86	9.0	62	7.0	48	5.5	38	5.0	34
		600	315	...	...	11.5	79	8.5	59	6.0	41	4.0	28	3.5	24
249.0	T7	RT	RT	47.0	324	26.0	179	14.5	100	11.5	79	11.0	76	11.0	76
		350	177	37.0	255	22.0	152	12.5	86	10.0	69	9.5	66	9.5	66
355.0	T71	RT	RT	...	...	21.0	145	15.0	103	12.0	83	11.0	76	10.5	72
		300	150	...	...	18.0	124	14.0	97	11.0	76	10.0	69	9.5	66
		400	205	...	...	17.0	117	13.0	90	9.5	66	7.5	52	7.0	48
		500	260	...	...	14.0	97	10.0	69	7.0	48	5.0	34	4.5	31
C355.0	T6	RT	RT	...	...	28.0	193	19.0	131	16.0	110	14.5	100	14.0	97
		300	150	...	...	27.0	186	18.0	124	13.5	93	12.5	86	12.0	83
		400	205	32.0	221	24.0	166	16.5	114	12.0	83	10.0	69	9.0	62
		500	260	25.0	172	18.0	124	11.5	79	7.5	52	5.5	38	5.0	34
		600	315	17.0	117	11.5	79	7.5	52	5.5	38	4.0	28	3.5	24
Permanent mold casting															
242.0	T571	RT	RT	34.0	234	26.0	179	20.0	138	16.5	114	15.5	107	15.0	103
		300	150	...	...	24.5	169	20.0	138	16.0	110	15.0	103	13.5	93
		400	205	25.0	172	18.5	128	13.0	90	9.5	66	8.5	59	8.0	55
		500	260	22.0	152	16.0	110	11.0	76	7.5	52	6.0	41	5.5	38
		600	315	18.0	124	13.0	90	8.5	59	5.5	38	4.0	28	3.5	24
333.0	T5	RT	RT	...	...	22.5	155	18.0	124	15.5	107	14.5	100	13.5	93
		300	150	...	...	20.0	138	15.5	107	11.5	79	10.0	69	9.5	66
		400	205	...	...	18.0	124	14.5	100	10.5	72	8.5	59	7.5	52
		500	260	...	...	15.5	107	12.0	83	8.5	59	6.5	45	6.0	41
		600	315	...	...	12.0	83	9.0	62	6.5	45	5.0	34	4.5	31
	T7	RT	RT	...	...	24.0	166	18.5	128	15.5	107	13.5	93	12.5	86
		300	150	...	...	22.0	152	17.0	117	12.5	86	10.0	69	9.5	66
		400	205	...	...	19.5	134	14.0	97	9.5	66	7.5	52	6.5	45
		500	260	...	...	17.0	117	12.5	86	8.5	59	6.0	41	5.5	38
		600	315	...	...	11.5	79	8.5	59	6.0	41	4.0	28	3.5	24
336.0	T551	RT	RT	...	...	21.0	145	18.0	124	16.0	110	14.5	100	13.5	93
		300	150	...	...	19.5	134	15.0	103	13.0	90	11.0	76	15.5	107
		400	205	...	...	16.0	110	12.5	86	10.0	69	8.5	59	8.0	55
		500	260	...	...	15.0	103	10.5	72	8.0	55	7.0	48	6.5	45
354.0	T6	RT	RT	50.0	345	40.0	276	31.0	214	25.5	176	21.0	145	19.5	134
		300	150	...	...	37.0	255	29.0	200	21.5	148	16.5	114	15.5	107
		400	205	...	...	31.0	214	22.0	152	15.0	103	10.0	69	8.5	59
		500	260	28.0	193	20.5	141	14.0	97	9.0	62	6.0	41	5.5	38
		600	315	14.0	97	11.0	76	8.0	55	6.0	41	4.5	31	4.0	28
355.0	T62	RT	RT	...	...	36.0	248	29.0	200	23.0	159	18.0	124	15.5	107
		300	150	...	...		0	21.0	145	16.0	110	12.0	83	...	...
		400	205	...	...	23.0	159	17.5	121	12.5	86	9.0	62	...	...
		600	315	...	...	10.5	72	7.0	48	5.0	34	3.5	24	...	...

(continued)

Metric values of strength determined by multiplying strengths originally determined in English units by conversion factor of 6.897. RT, room temperature. Source: Aluminum Association and Alcoa publications

Table 8.16 (continued)

		Test temperature		Fatigue strength at life of										Endurance limit at 5×10^8 cycles	
				10^4 cycles		10^5 cycles		10^6 cycles		10^7 cycles		10^8 cycles			
Alloy	Temper	°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
Permanent mold casting (continued)															
355.0	T71	RT	RT	...	...	27.0	186	21.0	145	17.0	117	14.5	100	13.0	90
		300	150	...	...	25.0	172	19.5	134	15.0	103	11.0	76	10.0	69
		400	205	...	...	21.0	145	16.0	110	12.0	83	8.5	59	8.0	55
		600	315	...	...	10.0	69	8.0	55	5.5	38	3.0	21	2.5	17
359.0	T61	RT	RT	43.0	297	34.0	234	27.0	186	21.5	148	17.5	121	16.5	114
		300	150	41.0	283	31.0	214	23.5	162	18.5	128	14.0	97	12.5	86
		400	205	34.0	234	26.0	179	18.0	124	11.5	79	6.0	41	4.0	28
Die casting															
380.0	F	RT	RT	...	...	28.0	193	22.0	152	20.5	141	20.0	138	20.0	138
		300	150	...	...	18.5	128	15.0	103	13.0	90	11.0	76	10.0	69
		400	205	...	...	15.0	103	11.0	76	8.5	59	7.5	52	7.0	48
		500	260	...	...	12.5	86	9.0	62	6.5	45	5.5	38	5.0	34

Metric values of strength determined by multiplying strengths originally determined in English units by conversion factor of 6.897. RT, room temperature. Source: Aluminum Association and Alcoa publications

summary are that the fatigue properties of permanent mold cast aluminum alloys may be expected to be superior to those of sand castings, the lowest band.

Further indication that the fatigue strengths of cast aluminum components may be expected to be inferior to those of wrought aluminum products are borne out by flexural fatigue ($R = 0.0$) tests of 220.0-T4 and 356.0-T6 sand cast beams, 218.0-F and 380.0-F die cast beams, and 6061-T6 wrought beams (Ref 21), shown in Fig. 8.4. The band of data for the cast beams falls consistently below the curve for 6061-T6.

Such generalized views of the differences in fatigue lives of cast and wrought aluminum alloys probably overlook the more basic fact that casting quality itself is the most important factor in determining fatigue life (just as it is for strength and toughness). Data reported by Promisel (Ref 22), reproduced in Fig. 8.5, demonstrate that the degree of porosity of 295.0 (regrettably not documented as to temper, but probably T6) has a direct bearing on fatigue strength; for the eight different degrees of porosity for which data are presented, fatigue strength rather consistently increases as the degree of porosity is decreased, that is, as casting quality increases.

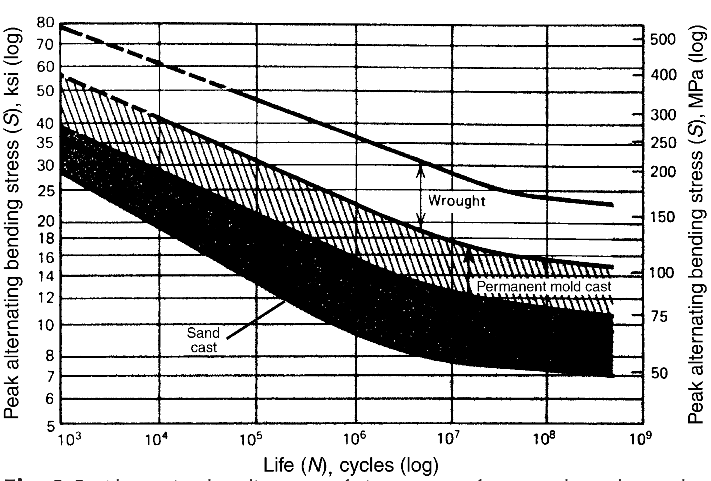

Fig. 8.3 Alternating bending stress fatigue curves for wrought and cast aluminum alloys. Source: Ref 20

While there are few data to demonstrate it, it is also therefore reasonable to expect that improvements in casting practices that lead to better soundness and minimal porosity, such as premium quality casting, squeeze casting, and semisolid casting, will result in improved fatigue properties. One indication of that is found in the work of Williams and Fisher (Ref 23), shown in Fig. 8.6, who found that the axial-stress fatigue strengths of A356.0-T6 squeeze castings consistently performed better than conventionally chill cast A356.0-T6 castings.

Further evidence of the effect of defects and discontinuities is illustrated by the work on hot isostatic pressing by Boileau and Wang discussed in Chapter 6.

8.4.2 *Influence of Stress Raisers on Fatigue Strength of Aluminum Castings*

As with wrought aluminum alloys, stress raisers such as notches or holes significantly reduce the fatigue strengths of aluminum castings. Data were presented in Section 8.3.4, under "Premium Engineered Castings," to show that fatigue strength decreases with increasing porosity, and notches represent an even more severe stress concentration. The *S-N* curves in Data Set 6, the results of which are summarized in Table 8.15, provide examples of the effects of severe machined notches (with theoretical stress concentration factors, $K_t > 12$) on fatigue strengths of representative casting alloys; in these cases, the notched specimen endurance limits are one-third to one-half those for the smooth specimens.

Sharp et al. (Ref 21) (Fig. 8.7) have shown that the sharp notch fatigue strengths of 355.0-T6 aluminum castings are about the same as, perhaps even slightly superior to, those of 6070-T6 and 7005-T53 wrought products. The significance of this is that, despite the smooth-specimen superiority of wrought products over castings, when real design discontinuities are present the fatigue prop-

erties of the various products may not differ significantly, and improving fatigue performance may be more a problem of reducing component stress concentrators and in the selection of an alloy or product form.

8.4.3 *Fatigue Strengths of Welded Aluminum Castings*

Few data are available to document the fatigue strengths of weldments in aluminum castings, but Sharp et al. (Ref 21) present

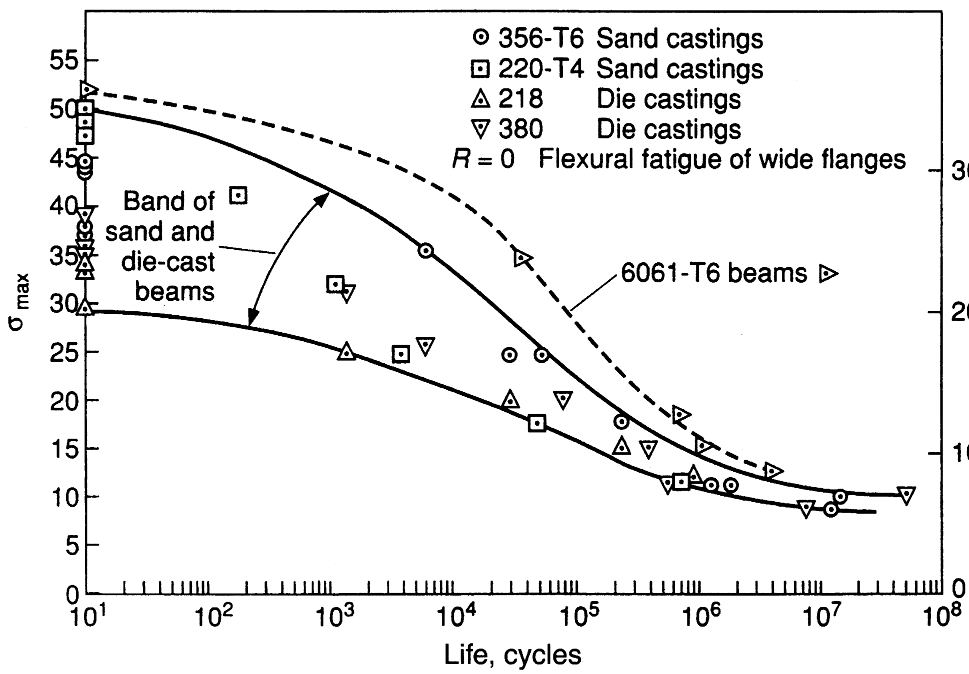

Fig. 8.4 Flexural fatigue properties (R = 0) of aluminum alloy beams produced from wrought and cast aluminum alloys. Source: Ref 20

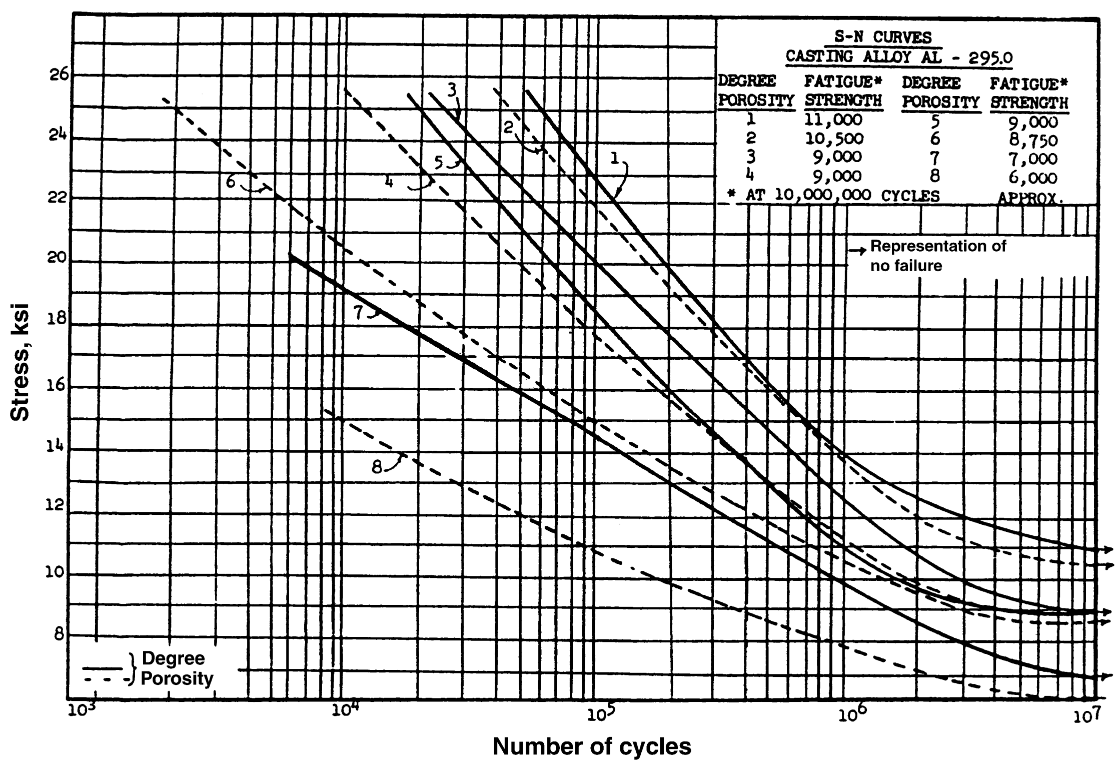

Fig. 8.5 Fatigue properties of 295.0 aluminum alloy castings with various degrees of porosity. Source: Ref 22

the results of axial-stress ($R = 0.0$) fatigue tests of 355.0-T6 casting welded together with 355.0 as filler metal and also 355.0-T6 welded to 5456-H321 with 4043 as filler metal, as in Fig. 8.8. There was no significant difference in fatigue strength of the two weld combinations, nor was there any significant effect of removing the weld bead or leaving it intact.

8.4.4 Design Fatigue Strengths for Aluminum Castings

MMPDS/MIL-HDBK-5H (Ref 15) includes strain-life fatigue curves for use in design of aluminum aircraft. For aluminum alloy castings, a curve is shown only for A201.0-T7, and those data are reproduced in Fig. 8.9. No other fatigue data for aluminum castings are presented.

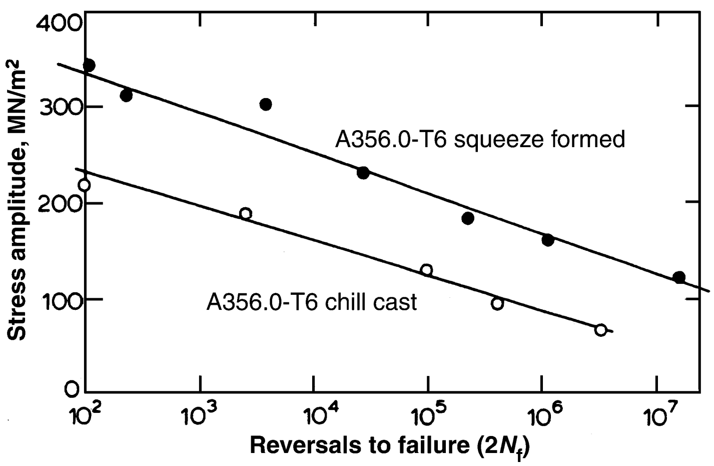

Fig. 8.6 Fatigue properties of conventionally cast and squeeze cast aluminum alloy A356.0-T6. Source: Ref 23

8.5 Fracture Resistance of Aluminum Alloys

Notch toughness, tear resistance, and plane-strain fracture toughness have been the primary measures used to assess the toughness of aluminum alloy castings (Ref 24). Because of the difficulty in getting valid fracture toughness tests from castings, more data are available for notch toughness and tear resistance, but representative data for all three are presented and discussed in the sections that follow.

8.5.1 Notch Toughness and Notch Sensitivity

One of the earliest approaches to the evaluation of the fracture characteristics of aluminum alloys was via tensile tests of specimens containing various types of stress raisers (Ref 24). The results from these tests were analyzed in terms of the theoretical stress-concentration factors. This approach, however, has not always been very useful in design, since the same theoretical stress concentration factors can be obtained with a great variety of different geometrical notch and specimen configurations, each of which has a unique influence on the numerical results of the tests; if design is the goal, the notched specimen must mirror the stress conditions in the component, including its stress raisers.

Therefore, the results of tensile tests of notched specimens have been used primarily to qualitatively merit rate aluminum alloys with respect to their notch toughness, that is, their ability to plastically deform locally in the presence of stress raisers and thus redistribute the stress. The notch tensile strength itself is of small value for this rating; the relationship of the notch tensile strength to the tensile properties is much more meaningful.

For many years, the criterion most often used from notch tensile test results was the notch-strength ratio, the ratio of the notch tensile strength to the tensile strength of the material. However, this ratio tells little about the relative abilities of alloys to deform

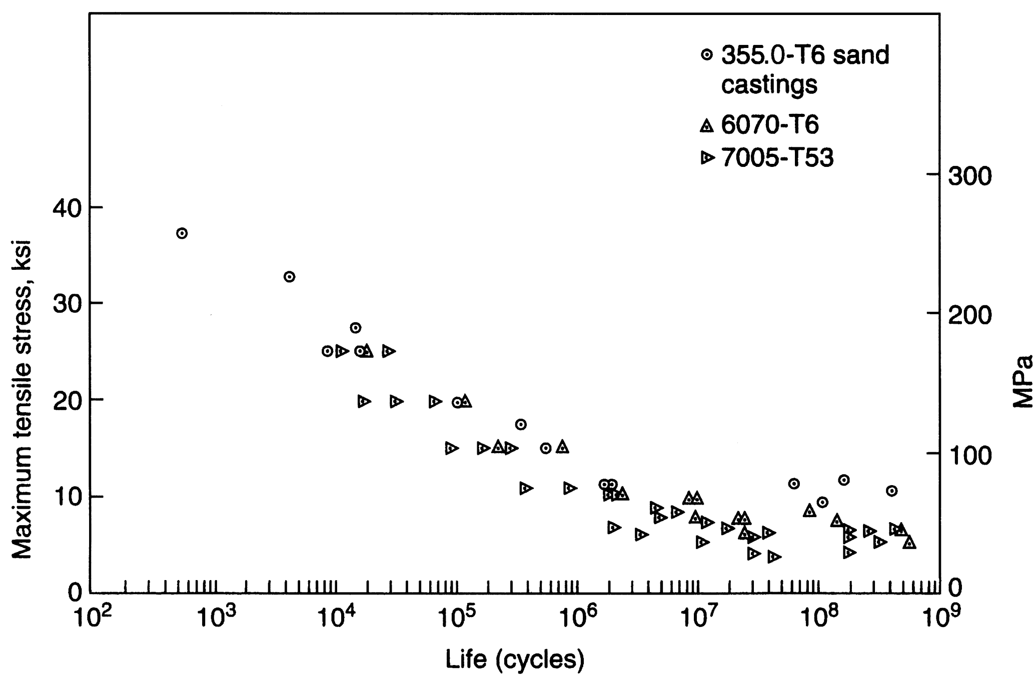

Fig. 8.7 Rotating beam ($R = -1.0$) fatigue properties of notched specimens from wrought and cast aluminum alloys. Source: Ref 21

plastically in the presence of stress raisers. In fact, for different notch geometries, it can indicate contradictory ratings (Ref 24). There are instances, of course, when the notch-strength ratio is useful, for example, when a measure of tensile efficiency of a specific structural member is required, or when the ultimate strength is the primary data taken for the smooth specimens, as in fatigue tests or stress rupture tests.

A more meaningful indication of the inherent ability of a material to plastically deform locally in the presence of a severe stress raiser is provided by the notch-yield ratio—the ratio of the notch tensile strength to the tensile yield strength (Ref 24). The yield strength, although arbitrarily defined, is a measure of the lowest stress at which appreciable plastic deformation occurs in a tensile test. Therefore, the relationship of the notch tensile strength to the yield strength tells more about the behavior of the material in the presence of a stress raiser than the ratio of the notch tensile strength to the tensile strength. If the notch tensile strength is appreciably above the yield strength (regardless of its relation to the tensile strength), the material has exhibited an ability to deform locally in the presence of the stress raiser.

If the notch tensile strength is appreciably below the yield strength, the fracture must have taken place without very much plastic deformation. For a specific notch design, this may or may not provide much specific design information, but as a relative measure of how several alloys behave in that situation, it is quite useful. Further indication of this fact is the experimental result that the notch-yield ratio provides rather consistent ratings of many alloys and tempers for a wide variety of notch geometries, and the ratings are consistent with those from fracture parameters, as described later.

While a number of different designs of notch have been used by different investigators, very sharp 60° V-notches provide the greatest discrimination among different alloys. In addition, such notches come close to representing the most severe unintentional stress raiser that is likely to exist in a structure: a crack. ASTM standards for notch tensile testing (Ref 25) call for notch-tip radii equal to or less than 0.0005 in. (0.013 mm), easily maintained in machining aluminum specimens (though quality assurance measurements are recommended).

Notch Toughness at Room Temperature. The specific design of notch for which data for a wide variety of casting alloys are available is shown in Appendix 3, Fig. A3.5. Representative data for various aluminum casting alloys with this design of specimen are given in Table 8.17 (Ref 24). Data for welds in various aluminum casting alloys are presented in Table 8.18. In all cases, the data were generated in accordance with ASTM E 602 (Ref 25).

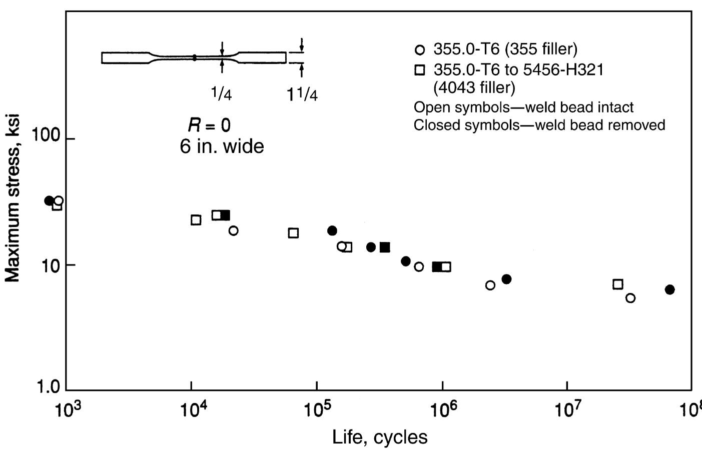

Fig. 8.8 Axial-stress (R = 0) fatigue properties of welded aluminum alloy castings. Source: Ref 21

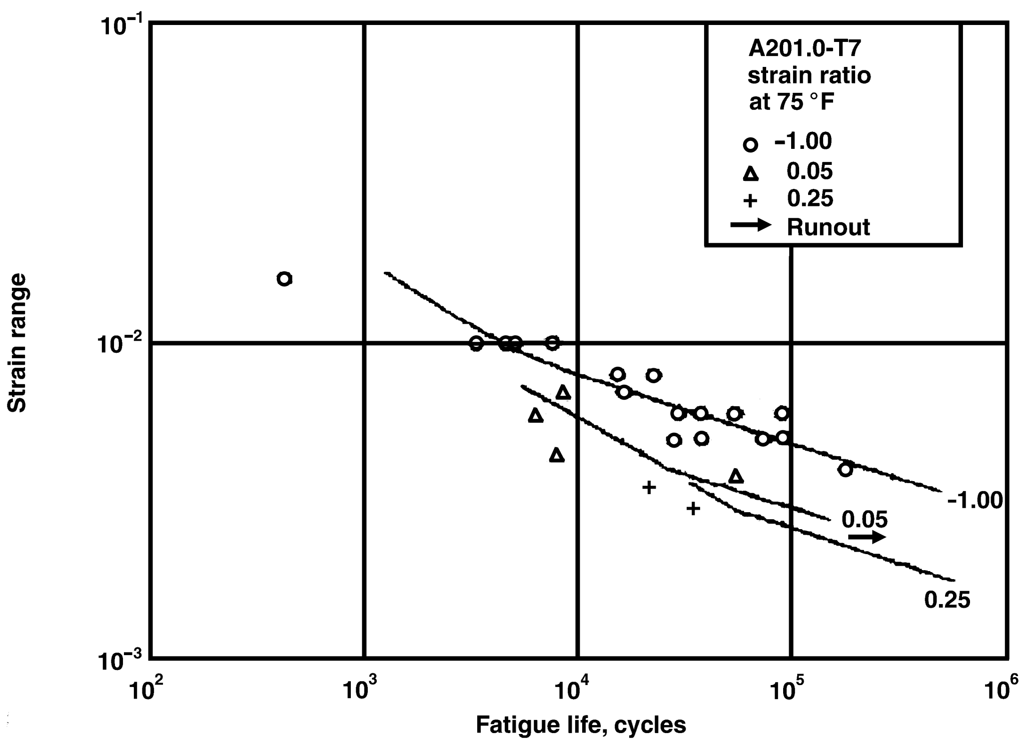

Fig. 8.9 Best-fit fatigue curves for aluminum alloy A201-T7 at various strain rates at 75 °F (24 °C). Source: Ref 14

Table 8.17 Representative notch toughness tests of cast aluminum alloys at room temperature

Specimens per Appendix 3, Fig. A3.5; each line is the average of two tests of a single lot of material.

Alloy and temper	Ultimate tensile strength, ksi	Ultimate tensile strength, MPa	Tensile yield strength(a), ksi	Tensile yield strength(a), MPa	Elongation in 2 in., %	Reduction of area, %	Notch tensile strength, ksi	Notch tensile strength, MPa	NTS/TS	NTS/YS
Sand casting										
240.0-F	33.8	233	26.0	179	1.4	2	22.5	155	0.67	0.87
242.0-T77	29.8	206	20.4	141	2.1	4	27.4	189	0.92	1.34
295.0-T6	42.0	290	27.1	187	6.4	10	47.4	327	1.13	1.75
308.0-F	25.0	172	18.5	128	1.8	2	22.1	152	0.88	1.19
X335.0-T6	37.3	257	23.4	161	8.6	12	38.2	263	1.02	1.63
	35.3	243	22.6	156			37.4	258	1.06	1.65
Average	**36.3**	**250**	**23.0**	**159**			**37.8**	**261**	**1.04**	**1.64**
356.0-T4	31.1	214	19.8	137	4.4	6	31.6	218	1.02	1.60
	29.4	203	17.6	121			31.3	216	1.07	1.78
Average	**30.2**	**208**	**18.7**	**129**			**31.4**	**217**	**1.04**	**1.69**
356.0-T6	38.6	266	32.6	225	2.2	3	37.4	258	0.97	1.15
356.0-T7	37.8	261	33.7	232	1.6	2	34.5	238	0.91	1.02
356.0-T71	28.8	199	20.2	139	5.0	. . .	32.0	221	1.11	1.59
	31.9	220	24.2	167			38.2	263	1.20	1.58
	29.4	203	20.7	143			30.6	211	1.04	1.46
Average	**30.0**	**207**	**21.7**	**150**			**33.6**	**232**	**1.12**	**1.54**
A356.0-T61	41.6	287	30.2	208	8.8	10	51.4	355	1.23	1.70
A356.0-T7	37.1	256	30.5	210	4.4	7	44.9	310	1.21	1.47
	37.6	259	33.2	229			38.2	263	1.02	1.15
Average	**37.4**	**258**	**31.8**	**219**			**41.6**	**287**	**1.12**	**1.31**
520.0-F	34.2	236	31.6	218	2.1	2	38.4	265	1.12	1.22
B535.0-F	41.2	284	21.2	146	12.9	13	43.8	302	1.06	2.06
	42.6	294	21.0	145			44.9	310	1.05	2.14
Average	**41.9**	**289**	**21.1**	**146**			**44.4**	**306**	**1.06**	**2.10**
A612.0-F	43.1	297	34.8	240	3.2	7	45.5	314	1.05	1.31
Permanent mold casting										
X335.0-T61	40.8	281	28.4	196	8.5	13	45.7	315	1.12	1.61
	35.6	246	25.6	177	3.5	4	40.4	279	1.14	1.58
Average	**38.2**	**263**	**23.8**	**164**	**6.0**		**42.3**	**297**	**1.13**	**1.60**
354.0-T62	50.1	346	45.5	314	1.1	3	54.2	374	1.08	1.19
	47.8	330	44.3	306	0.9	2	51.2	353	1.07	1.16
Average	**49.0**	**340**	**44.9**	**310**	**1.0**	**2**	**52.7**	**364**	**1.08**	**1.18**
C355.0-T7	37.0	255	31.0	214	2.1	4	43.4	299	1.17	1.40
	41.0	283	30.4	210	2.5	6	41.8	288	1.02	1.38
Average	**39.0**	**269**	**30.7**	**212**	**2.3**	**5**	**42.5**	**294**	**1.10**	**1.39**
356.0-T6	35.8	247	31.1	214	1.4	3	4.3	30	1.17	1.38
356.0-T7	28.4	196	21.4	148	4.3	6	35.3	243	1.24	1.65
	29.6	204	22.0	152	3.2	6	34.3	237	1.16	1.56
Average	**29.8**	**206**	**22.0**	**152**	**5.0**	**8**	**34.8**	**240**	**1.20**	**1.60**
A356.0-T61	39.4	272	30.8	212	4.3	7	47.8	330	1.21	1.55
	41.7	288	30.4	210	7.5	8	45.4	313	1.22	1.75
Average	**40.6**	**280**	**30.6**	**211**	**5.9**	**8**	**46.6**	**322**	**1.22**	**1.65**
A356.0-T62	40.9	282	36.7	253	2.1	6	46.2	319	1.13	1.26
	43.6	301	36.3	250	3.9	. . .	43.8	302	1.00	1.21
Average	**42.2**	**291**	**36.5**	**252**	**3.0**	**6**	**45.0**	**310**	**1.06**	**1.24**
A356.0-T7	28.2	194	21.4	148	5.3	9	36.9	254	1.31	1.72
359.0-T62	46.2	319	43.2	298	1.2	3	49.7	343	1.08	1.15
	47.4	327	43.1	297	1.6	4	42.9	296	0.91	1.00
Average	**34.7**	**239**	**43.2**	**298**	**1.4**	**4**	**46.3**	**324**	**1.00**	**1.08**
A444.0-F	23.2	160	9.7	67	22.2	37	28.6	197	1.23	2.96
	22.5	155	9.6	66	15.7	21	27.8	192	1.25	2.90
Average	**22.8**	**157**	**9.6**	**66**	**19.0**		**28.2**	**194**	**1.24**	**2.96**
A444.0-T4	23.0	159	8.0	55	24.4	36	30.8	212	1.39	3.72
Premium engineered casting										
A201.0-T7	63.8	440	58.1	401	7.0	10	79.6	549	1.25	1.37
224.0-T7	54.1	373	41.0	283	6.6	9	64.5	445	1.19	1.57
	54.2	374	38.6	266	6.6	9	65.9	455	1.22	1.71
Average	**54.2**	**374**	**39.8**	**274**	**6.6**	**9**	**65.0**	**448**	**1.20**	**1.64**

(continued)

NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For tensile yield strength, offset = 0.2%.

Table 8.17 (continued)

Alloy and temper	Ultimate tensile strength		Tensile yield strength(a)		Elongation in 2 in., %	Reduction of area, %	Notch tensile strength		NTS/TS	NTS/YS
	ksi	MPa	ksi	MPa			ksi	MPa		
Premium engineered casting (continued)										
249.0-T7	57.6	397	49.2	339	7.4	11	69.3	478	1.20	1.41
354.0-T6	48.0	331	43.0	297	1.2	1	45.4	313	0.95	1.06
C355.0-T6	43.6	301	40.8	281	1.0	1	43.4	299	1.00	1.06
C355.0-T61	43.6	301	30.3	209	6.4	9	52.6	363	1.21	1.74
A356.0-T6	41.6	287	30.2	208	8.8	10	51.4	355	1.23	1.70
A357.0-T6	52.0	359	43.2	298	4.5	6	48.4	334	0.93	1.12
A357.0-T61	51.2	353	40.0	276	11.4	13	56.2	388	1.10	1.41
A357.0-T62	53.9	372	46.4	320	5.3	7	59.4	410	1.10	1.28

NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For tensile yield strength, offset = 0.2%.

Relative rankings of the casting alloys are presented in the bar graphs in Fig. 8.10, segregated by sand castings (Fig. 8.10a), permanent mold castings (Fig. 8.10b), and premium-strength castings (Fig 8.10c).

Alloy A444.0-F permanent mold castings, with the lowest yield strength of the entire group, ranks highest. Otherwise, for the respective groups, 295.0-T6 and B535.0-F rank highest among sand cast alloys; A356.0-T6 and -T71 rank highest among permanent mold castings; and 224.0-T7, A356.0-T6, and C355.0-T61 rank highest among the premium-strength castings. Among the higher-strength casting alloys, the premium quality castings (that is, sand castings made with special care to provide high metal chill rates in highly stressed regions) rate well, and A356.0-T6 consistently has higher toughness than does 356.0-T6, the positive effect of its higher purity (i.e., lower content of impurities such as iron).

Looking at the relationship between notch-yield ratio (NYR) and tensile yield strength also provides interesting information for castings (Fig. 8.11), most notably the relationship of their performance to that of wrought alloys.

Alloys A444.0-F and B535.0-F have among the best combinations of strength and notch toughness, as do the premium-strength castings in the T61, T62, and T7 tempers; they fall in or near lower edge of the band for wrought alloy data. However, the other sand and permanent mold cast alloys fall below the wrought alloy band; of the latter groups, the permanent mold castings generally exhibit the best performance.

Relative rankings for welds in aluminum alloy castings based on notch-yield ratio (Table 8.18) are shown in Fig. 8.12.

Welds in A444.0-F have the highest notch-yield ratios by a considerable margin, not surprising with their low strength. Alloys 354.0-T62 and C355.0-T6 are within a fairly narrow range, with C355.0-T6 welds being slightly superior.

Once again, looking at the data on the basis of NYR versus tensile yield strength (TYS) as in Fig. 8.13 reveals additional information.

For the two higher-strength alloys, 354.0-T62 and C355.0-T6, there is also an indication that welds made with 5356 and 5556 filler alloys have somewhat better combinations of strength and tough-

Table 8.18 Representative notch toughness test results of welds in cast aluminum alloys at room temperature

Specimens per Appendix 3, Fig. A3.5; each line represents the average of duplicate tests on one lot of material. Joint efficiencies based on typical values for parent alloys. No postweld thermal treatment

Alloy and temper combination	Filler alloy	Ultimate tensile strength		Tensile yield strength(a)		Elongation in 2 in., %	Reduction of area, %	Joint strength efficiency, %	Location of fracture(b)	Notch tensile strength		NTS/TS	NTS/YS
		ksi	MPa	ksi	MPa					ksi	MPa		
A444.0-F to A444.0-F	4043	23.8	164	9.5	66	12.1	22	100	B	27.5	190	1.15	2.90
A444.0-F to 6061-T6	4043	24.0	166	11.4	79	5.7	23	100	B	29.3	202	1.22	2.51
A444.0-F to 5456-H321	5556	24.1	166	12.2	84	12.1	27	100	B	29.5	203	1.22	2.42
354.0-T62 to 354.0-T6	4043	37.8	261	21.5	148	6.4	10	76	A	32.0	221	0.85	1.48
354.0-T62 to 6061-T6	4043	30.8	212	19.0	131	9.3	39	62	C	28.7	198	0.93	1.51
354.0-T62 to 5456-H321	5556	37.7	260	24.6	170	3.6	5	75	A	37.7	260	1.00	1.53
C355.0-T61 to 6061-T6	4043	28.9	199	19.3	133	7.1	32	66	C	34.5	238	1.19	1.79
C355.0-T61 to 5456-H321	5556	35.4	244	24.4	168	3.6	5	81	A	40.5	279	1.15	1.66

NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For joint yield strength, offset = 0.2%, over a 2 in. gage length. (b) Location of fracture of unnotched specimens: A, through weld; B, ½ to 2½ in. from weld; C, edge of weld

ness than do welds made with 4043; this is also consistent with the case for wrought alloys. In low-strength, high-toughness alloy A444.0-F, choice of filler alloy made little difference.

The notch toughness of most welds as measured by NYR is generally somewhat less than that for parent metal of the same strength, the principal exceptions being welds made with the 5xxx series filler alloys. Many data for 4043 welds fall well below the band for wrought alloys; a notable exception is when the 4043 weld in 6061-T6 was heat treated and aged after welding.

Notch Toughness at Subzero Temperatures. The results of notch tensile tests of several aluminum casting alloys at subzero temperatures are presented in Table 8.19. Data from these tests are plotted in Fig. 8.14 as a function of test temperature for sand cast alloys at subzero temperatures (Fig. 8.14a and b), permanent mold cast alloys (Fig. 8.14c), and premium-strength sand cast alloys (Fig. 8.14d).

From Fig. 8.14, it can be seen that the 3xx.0 and 4xx.0 casting alloys rather consistently retain most or all of their toughness at subzero temperatures, even to –423 °F (–253 °C) and –452 °F (–269 °C). Alloy A444.0-F (Fig. 8.14c), with its relatively low yield strength, showed an exceptionally high NYR, at or above 2.5, even at –320 °F (–196 °C). From the notch tensile data in Fig. 8.14(d), it is also clear that A356.0-T61 performed quite well even at –452 °F (–269 °C). Other casting alloys, notably the 2xx.0 and 5xx.0 series, generally show a consistent and more rapidly decreasing toughness with decrease in temperature.

When the notch-yield ratios for cast alloys are viewed on the basis of yield strength level (Fig 8.15), A444.0-F exhibits exceptionally high toughness and, among the higher-strength alloys, the premium-strength cast alloys have the most consistently superior strength-toughness combination, similar to the case at room temperature.

The performance of the permanent mold castings is generally nearly as good as the premium-strength castings and, in fact, B535.0

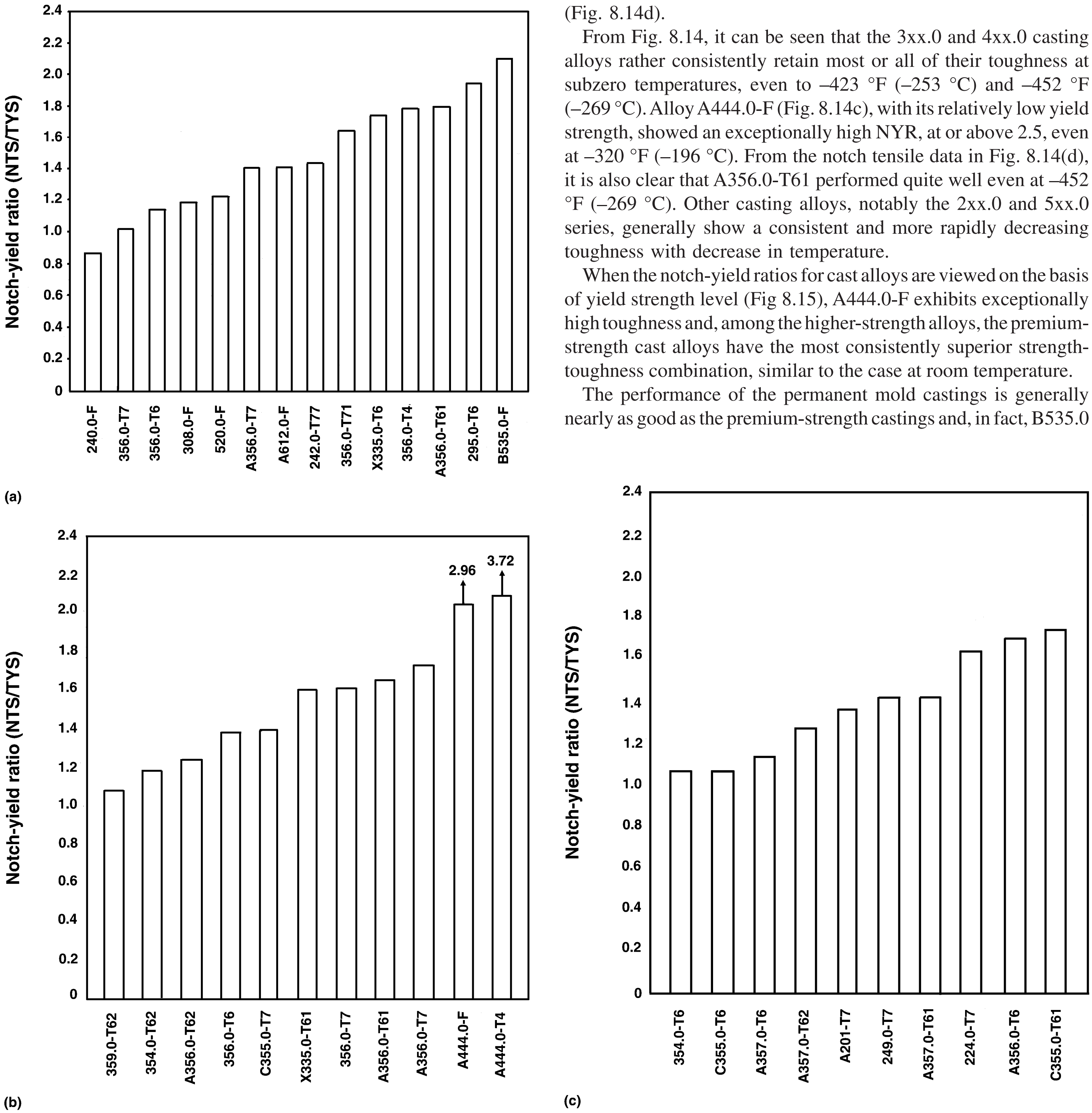

Fig. 8.10 Relative rankings of notch toughness of aluminum casting alloys based upon notch-yield ratio. (a) Sand castings. (b) Permanent mold castings. (c) Premium engineered castings

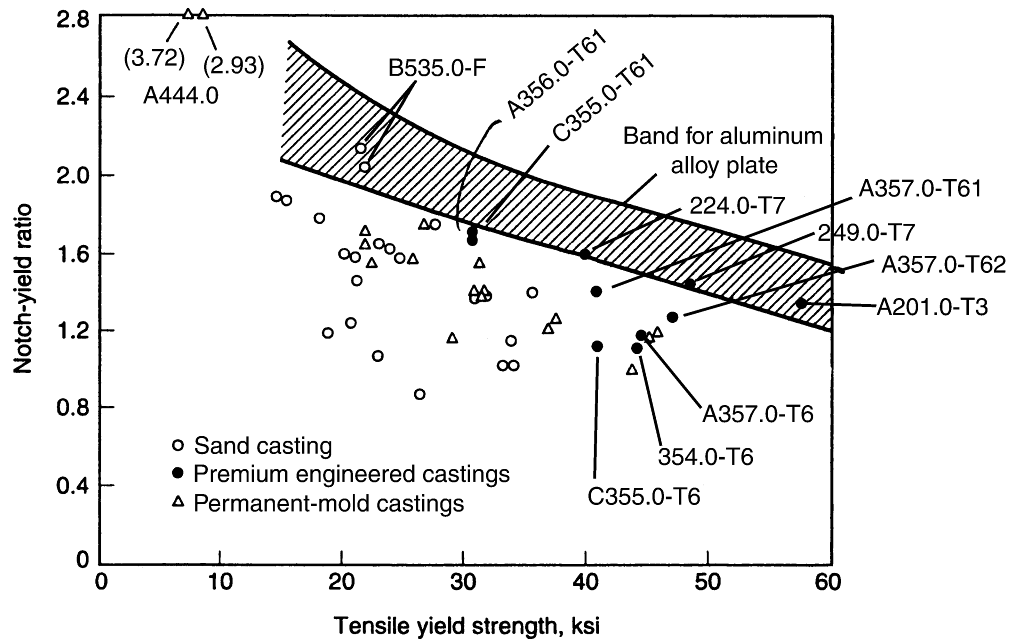

Fig. 8.11 Notch-yield ratio versus tensile yield strength for selected aluminum alloy castings

and A356.0 permanent mold castings essentially match the performance of the premium-strength castings. The conventionally cast sand castings rather consistently exhibit the poorest performance.

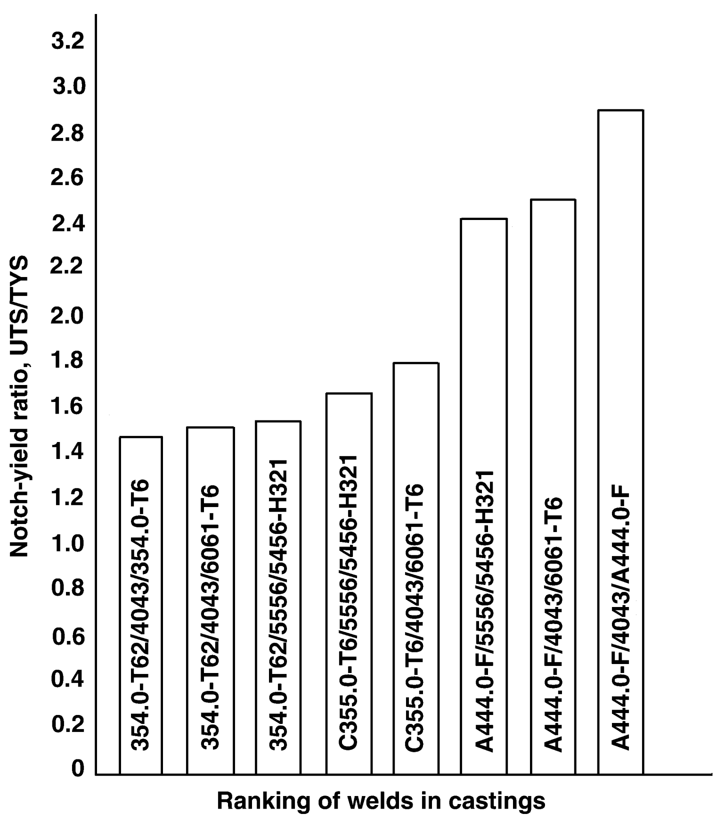

Fig. 8.12 Rankings of notch toughness of welds in aluminum casting alloys based upon notch-yield ratio for combinations of casting alloys and filler alloys (middle number)

When selecting cast alloys for cryogenic service, it seems especially important to pay careful attention to the casting process as well as the alloy itself; high-quality casting processes yield superior combinations of strength and toughness.

Data for welds in cast alloys at subzero temperatures are presented in Table 8.20, and the NYRs are plotted as a function of temperature in Fig. 8.16.

Both 4043 and 5556 welds exhibited NYRs about the same at temperatures down to –320 °F (–196 °C) as at room temperature. At lower temperatures, both filler alloys exhibited some significant reduction, but in all cases, NYRs were above 1.0, even at –452 °F (–269 °C).

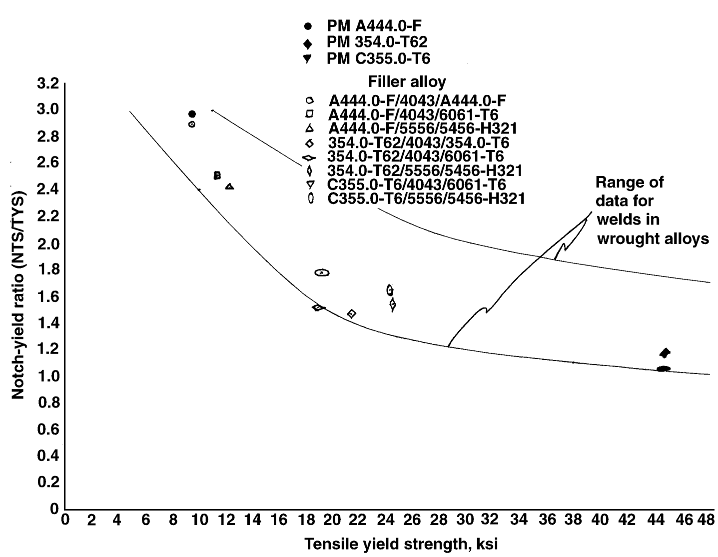

Fig. 8.13 Notch-yield ratio versus tensile yield strength for welds in aluminum alloy castings for combinations of casting alloys and filler alloys (middle number)

Table 8.19 Representative notch toughness test results of cast aluminum alloys at subzero temperatures

Tests of single specimen per Appendix 3, Fig. A3.5 at each temperature

Alloy and temper	Test temperature, °F	Ultimate tensile strength		Tensile yield strength(a)		Elongation in 2 in., %	Reduction of area, %	Notch tensile strength		NTS/TS	NTS/YS
		psi	MPa	psi	MPa			psi	MPa		
Sand casting											
208.0-F	RT	25.0	172	18.5	128	1.8	2	25.2	174	1.01	1.36
	–112	26.2	181	21.7	150	2.0(b)	0(b)	21.6	149	0.82	1.00
	–320	30.6	211	30.2	208	1.3	0	21.7	150	0.71	0.72
240.0-F	RT	33.8	233	26.0	179	1.4	2	29.9	206	0.88	1.15
	–112	32.8	226	22.7	157	(c)	(c)	19.4	134	<0.58	0.75
	–320	36.8	254	32.4	223	(c)	(c)	17.4	120	<0.47	0.54
242.0-T77	RT	29.8	206	20.4	141	2.1	4	29.0	200	0.97	1.42
	–112	32.8	226	22.7	157	(c)	(c)	26.0	179	<0.81	1.17
	–320	32.8	226	26.8	185	(c)	(c)	27.7	191	<0.84	1.03
295.0-T6	RT	42.0	290	27.1	187	6.4	10	43.5	300	1.04	1.60
	–112	45.5	314	32.0	221	6.0	5	58.0	400	1.08	1.45
	–320	53.7	370	39.9	275	5.0	5	58.0	400	1.08	1.45
X335.0-T6	RT	37.3	257	23.4	161	8.6	12	38.2	263	1.02	1.63
	–112	42.3	292	27.4	189	8.0	10	43.0	297	1.02	1.57
	–320	51.6	356	32.1	221	7.6	10	45.6	315	0.88	1.42
356.0-T4	RT	31.1	214	19.8	137	4.4	6	31.6	218	1.02	1.60
	–112	36.6	252	23.4	161	4.4	6	37.6	259	1.04	1.61
	–320	40.8	281	27.2	188	2.7	3	42.2	291	1.04	1.55
356.0-T6	RT	38.6	266	32.6	225	2.2	3	37.4	258	0.97	1.15
	–112	43.1	297	35.8	247	2.7	2	40.0	276	0.93	1.12
	–320	47.5	328	39.2	270	2.7	2	44.0	303	0.93	1.13
356.0-T7	RT	37.8	261	33.7	232	1.6	2	34.5	238	0.91	1.02
	–112	41.4	286	34.4	237	2.0	2	38.8	268	0.94	1.13
	–320	45.1	311	38.8	268	1.3	0	43.1	297	0.96	1.11
356.0-T71	RT	28.8	199	20.2	139	5.0	. . .	32.0	221	1.11	1.59
	–112	32.2	222	22.2	153	4.4	5	29.6	204	0.92	1.34
	–320	37.4	258	25.3	174	3.0	2	34.4	237	0.92	1.36
A356.0-T61	RT	41.6	287	30.2	208	8.8	10	51.4	355	1.23	1.70
	–112	48.2	332	34.8	240	8.9	10	55.2	381	1.15	1.59
	–320	51.7	357	38.0	262	4.0	4	59.8	412	1.15	1.57
	–452	66.0	455	48.0	331	7.1	9	71.9	496	1.09	1.50
A356.0-T7	RT	37.1	256	30.5	210	4.4	7	44.9	310	1.21	1.47
	–112	40.0	276	31.7	219	4.4	5	41.0	283	1.02	1.29
	–320	45.6	315	35.2	243	3.4	4	44.0	303	0.96	1.25
B535.0-F	RT	41.2	284	21.2	146	12.9	13	43.8	302	1.06	2.07
	–112	41.6	287	22.3	154	10.0	11	42.4	292	1.06	1.90
	–320	37.3	257	25.5	176	3.7	5	35.5	245	0.95	1.39
	–423	30.8	212	28.1	194	0.8	1	20.0	138	0.65	0.71
520.0-F	RT	34.2	236	31.6	218	2.1	2	38.4	265	1.12	1.22
	–112	41.6	287	37.4	258	1.3	1	27.9	192	0.79	0.75
	–320	39.6	273	39.6(d)	273(d)	0.7	0	27.2	188	0.69	0.69
A612.0-F	RT	43.1	297	34.8	240	3.2	7	45.5	314	1.05	1.31
	–112	45.5	314	41.0	283	2.7	2	50.8	350	1.12	1.24
	–320	53.2	367	49.0	338	2.4	3	51.0	352	0.96	1.04
Permanent mold casting											
X335.0-T61	RT	40.8	281	28.4	196	8.5	13	45.7	315	1.12	1.61
	–112	40.1	277	29.2	201	4.6	7	47.2	326	1.18	1.62
	–320	45.7	315	31.0	214	5.3	5	53.4	368	1.18	1.72
	–423	54.0	372	35.8	247	5.0	. . .	58.3	402	1.08	1.63
354.0-T62	RT	50.1	346	45.5	314	1.1	3	54.2	374	1.08	1.19
	–112	54.4	375	45.6	315	1.3	2	53.2	367	0.98	1.17
	–320	61.0	421	48.7	336	1.3	2	56.4	389	0.92	1.16
	–423	60.2	415	56.1	387	0.8	1	57.2	395	0.95	1.02
356.0-T6	RT	36.8	254	31.1	214	1.0	. . .	43.0	297	1.17	1.38
	–112	42.0	290	34.1	235	3.7	5	41.4	286	0.98	1.21
	–320	45.7	315	36.5	252	3.2	4	45.0	310	0.98	1.23

(continued)

RT, room temperature; NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For yield strength, offset = 0.2%. (b) Broke outside middle third. (c) Broke in threads. (d) Broke before reaching 0.2%

Table 8.19 (continued)

Alloy and temper	Test temperature, °F	Ultimate tensile strength, psi	Ultimate tensile strength, MPa	Tensile yield strength(a), psi	Tensile yield strength(a), MPa	Elongation in 2 in., %	Reduction of area, %	Notch tensile strength, psi	Notch tensile strength, MPa	NTS/TS	NTS/YS
Permanent mold casting (continued)											
356.0-T7	RT	28.4	196	21.4	148	4.3	7	35.3	243	1.24	1.65
	–112	32.6	225	24.3	168	3.7	5	37.2	257	1.14	1.53
	–320	37.3	257	25.6	177	3.0	4	39.9	275	1.07	1.56
A356.0-T61	RT	39.4	272	30.8	212	4.3	. . .	47.8	330	1.21	1.55
	–112	41.9	289	32.6	225	3.7	6	47.7	329	1.14	1.46
	–320	49.4	341	35.8	247	4.4	6	52.6	363	1.07	1.47
A356.0-T62	RT	40.9	282	36.7	253	2.1	6	46.2	319	1.13	1.26
	–112	45.2	312	39.6	273	3.0	5	49.8	343	1.10	1.26
	–320	48.6	335	41.4	286	3.0	5	57.9	399	1.19	1.40
	–423	5.5	38	45.3	312	3.5	3	63.3	437	1.15	1.40
A356.0-T7	RT	28.2	194	21.4	148	5.3	9	36.9	254	1.31	1.72
	–112	35.4	244	25.8	178	5.7	8	43.9	303	1.24	1.70
	–320	42.7	295	28.5	197	6.4	7	47.1	325	1.10	1.65
359.0-T62	RT	46.2	319	43.2	298	1.2	3	49.7	343	1.08	1.15
	–112	52.4	361	47.3	326	2.0	4	49.8	343	0.95	1.05
	–320	57.7	398	49.5	341	1.6	4	49.8	343	0.86	1.01
A444.0-F	RT	23.2	160	9.7	67	22.2	37	28.6	197	1.23	2.95
	–112	26.2	181	10.0	69	19.7	24	30.4	210	1.16	3.04
	–320	37.6	259	12.1(b)	83(d)	13.3(b)	12(b)	32.0	221	0.85	2.64
Premium engineered casting											
C355.0-T61	RT	43.6	301	30.3	209	6.4	8	52.6	363	1.21	1.74
	–112	48.4	334	33.2	229	7.5	8	56.6	390	1.17	1.7
	–320	54.4	375	39.4	272	5.4	6	62.7	432	1.15	1.59
A356.0-T61	RT	41.6	287	30.2	208	8.8	10	51.4	355	1.23	1.7
	–112	48.2	332	34.8	240	8.9	10	55.2	381	1.15	1.59
	–320	51.7	357	38.0	262	4.0	4	59.8	412	1.15	1.57
A357.0-T61	RT	51.2	353	40.0	276	11.4	13	56.2	388	1.10	1.41
	–112	54.4	375	43.4	299	4.0	5	58.2	401	1.08	1.35
	–320	61.5	424	47.0	324	4.0	4	59.4	410	0.96	1.27
A357.0-T62	RT	51.2	353	44.4	306	2.5	4	55.4	382	1.08	1.25
	–112	53.1	366	46.7	322	2.1	3	55.2	381	1.04	1.18
	–320	62.2	429	49.3	340	2.5	4	59.7	412	0.96	1.21

RT, room temperature; NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For yield strength, offset = 0.2%. (b) Broke outside middle third. (c) Broke in threads. (d) Broke before reaching 0.2%

Viewing the data for welds at –320 °F (–196 °C) on the basis of NYR versus joint yield strength (JYS), as in Fig. 8.17, C355.0-T6 welded with either 4043 or 5456 exhibits a fair level of toughness for its high strength level.

All of the welds fall within the range of data for unwelded castings of the same alloys, reinforcing the point that even at temperatures as low as –320 °F (–196 °C) there is no deterioration in the strength-toughness combination associated with the welds. At the lowest temperature for which data were obtained (–452 °F, or –270 °C), A444.0-F welded with 4043 stands out and, of the higher strength alloys, C355.0-T61 welded with 5456 exhibits the highest toughness for its strength level.

8.5.2 Tear Resistance

A tear test of the type described in ASTM B 871 (Ref 26) was developed at Alcoa Laboratories to more discriminantly evaluate the fracture characteristics of the aluminum alloys in various tempers (Ref 24). As shown in Fig. 8.18, values of the energies required to initiate and propagate cracks in small sharply edge-notched specimens (Appendix 3, Fig. A3.6) are determined from measurements of the appropriate areas under the autographic load-deformation curves developed during the tests. The unit propagation energy is equal to the energy required to propagate the crack divided by the initial net area of the specimen, and it is the primary criterion of tear resistance obtained from the tear test.

The unit propagation energy, more than data from notch tensile tests, provides a measure of that combination of strength and ductility that permits a material to resist crack growth under either elastic or plastic stresses. The "tear strength," the maximum nominal direct-and-bending stress developed by the tear specimen, is also calculated, and the ratio of this tear strength to the yield strength provides a measure of notch toughness; it is referred to as the tear-yield ratio.

The usefulness of the data from this test is not dependent on the development of rapid crack propagation or fracture at elastic stresses. Therefore, the test can be used for all aluminum alloys, even very ductile, tough alloys.

While the results of tear tests are not greatly dependent on specimen thickness in the range from about 0.063 in. (1.6 mm) to about 0.125 in. (3.2 mm), all test results reported herein were obtained on specimens 0.100 ± 0.005 in. (2.5 ± 0.13 mm) in thickness. Other dimensions were maintained within the tolerances in Appendix 3, Fig A3.6. It is also appropriate to note that tear test results may be dependent on testing machine characteristics. All of the results reported herein were obtained on 50,000 lbf (2.2×10^5 N) Tinius Olsen hydraulic testing machines.

Representative data are shown in Table 8.21 for a variety of cast aluminum alloys with 0.100 in. (2.5 mm) thick specimens machined from ½ to 1 in. (12 to 25 mm) thick cast slabs.

Ratings of the cast alloys and tempers based on the values of unit propagation energy are shown in Fig. 8.19, and the relationship between unit propagation energy (UPE) to TYS is shown in Fig. 8.20. The relationship between UPE to TYS for wrought aluminum alloys is shown as a band for comparison.

While it is obvious that low-strength alloys A444.0 and B535.0 have exceptionally high tear resistance compared to the other cast alloys as defined by UPE, Fig. 8.20 also reveals that:

- Sand cast alloy B535.0-F has tear resistance in the same range as wrought alloy plate of the same strength level and a much better combination of UPE and TYS than most other casting alloys.

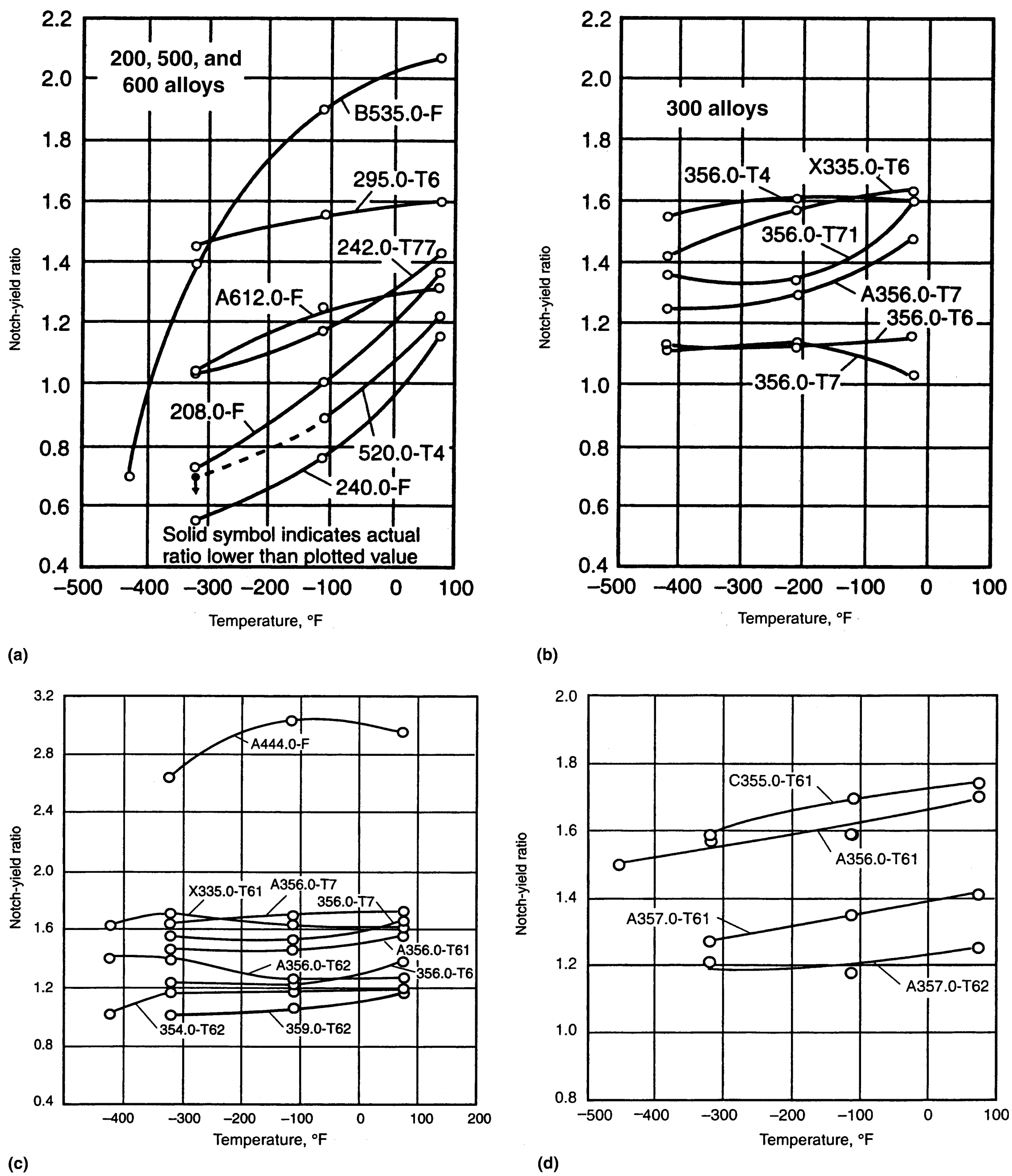

Fig. 8.14 Notch-yield ratio as a function of temperature for aluminum alloy castings. (a) Sand castings, 2xx.0, 5xx.0, and 6xx.0 alloys. (b) Sand castings, 3xx.0 alloys. (c) Permanent mold castings. (d) Premium engineered castings

- Among the higher-strength castings, the premium engineered castings consistently have among the best combinations of UPE and TYS, especially at relatively high strength levels.
- Permanent mold cast alloys generally fall in the intermediate range, with the notable exceptions that 354.0-T62 and 359.0-T62 essentially match the performance of the premium-strength cast alloys (and, in fact, could be considered premium engineered castings based on AMS-A-21180).
- With the exception of B535.0-F, sand castings generally have among the poorest combination of strength and toughness.

Representative tear test data for welds in cast aluminum alloys are shown in Table 8.22. Ratings of the welded cast alloys and tempers based on the values of unit propagation energy are shown in Fig. 8.21.

For welds in cast alloys, the tear resistance of welds made with 5xxx filler alloys are generally appreciably higher than those of welds made with high-silicon 4043 filler alloy. As in the case with notch toughness data, there are a few exceptions, notably in joints between 6061-T6 plate and 356.0-T6 or -T7 sand castings; in these cases, the high silicon in the 3xx.0 castings may be overwhelming the inherent high toughness of the 5xxx type filler alloys (although this was not reflected in the A356.0/6061 joints made with 5556).

An analysis of welds in castings based on UPE versus TYS is not available because joint yield strengths were not reported and a plot cannot be made. However, a scan of the data in Table 8.22 illustrates that 4043 welds in castings and 5556 welds in high-silicon castings generally provide lower toughness than other combinations of filler and parent alloys.

In general, one can conclude that for applications where high toughness is critical for joining aluminum castings, 5xxx filler alloys would be recommended, and 4043 filler alloy should be avoided except perhaps in the case of high-silicon casting alloys.

8.5.3 Fracture Toughness

The results of plane-strain fracture toughness tests of several aluminum castings are given in Table 8.23 (Ref 19, 24). The specimens used were of the design shown in Appendix 3, Fig. A3.7.

Background on the development and application of fracture mechanics to design is presented in Ref 24 and the other references cited therein. Very briefly summarized, it was through the work of A.A. Griffith, G.R. Irwin, and ASTM Committee E-24 on Fracture

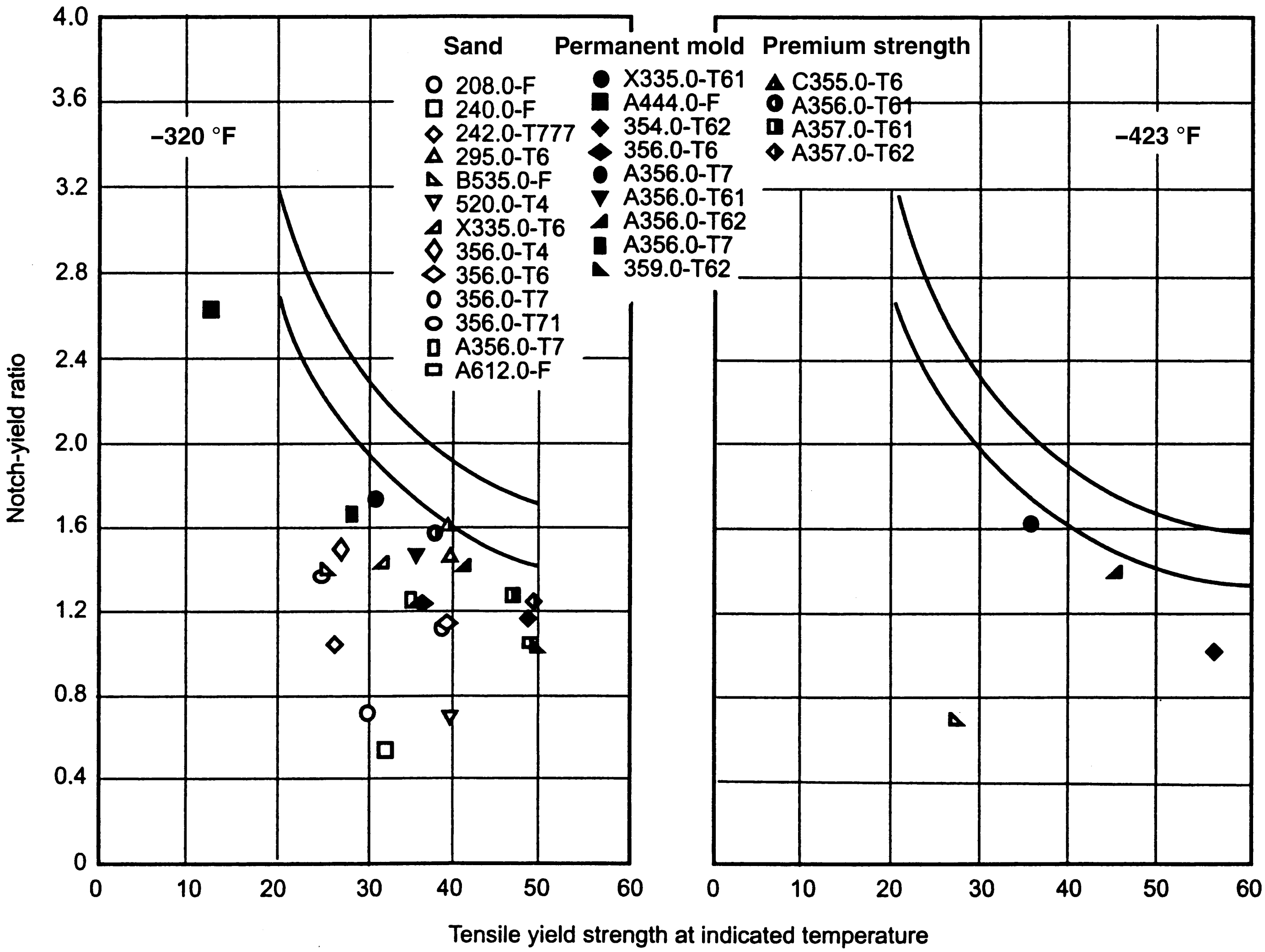

Fig. 8.15 Notch-yield ratio versus tensile yield strength for aluminum casting alloys at –320 °F (–196 °C) and –423 °F (–253 °C)

Table 8.20 Notch toughness tests of representative welds in aluminum alloy sand castings at subzero temperatures

Specimens per Appendix 3, Fig. A3.5; each line represents the average of duplicate tests on one lot of material. Joint efficiencies based on typical values for parent alloys. No postweld thermal treatment

Alloy and temper combination	Filler alloy	Test temperature, °F	Ultimate tensile strength, ksi	Ultimate tensile strength, MPa	Tensile yield strength(a), ksi	Tensile yield strength(a), MPa	Elongation in 2 in., %	Reduction of area, %	Jointmb;0 strength efficiency, %	Location of fracture(b)	Notch tensile strength, ksi	Notch tensile strength, MPa	NTS/TS	NTS/YS
A444.0-F to A444.0-F	4043	RT	23.8	164	9.5	66	12.1	22	100	B	27.5	190	1.15	2.90
		−112	26.1	180	10.0	69	14.3	26	100	B	31.7	219	1.21	3.17
		−320	33.5	231	11.5	79	6.4	9	89	B	38.1	263	1.14	3.31
		−452	48.6	335	18.0	124	10.0	13	(c)	A	40.4	279	0.83	2.24
A444.0-F to 6061-T6	4043	RT	24.0	166	11.4	79	5.7	23	100	B	29.3	202	1.22	2.51
		−320	34.7	239	14.8	102	7.1	9	92	B	34.1	235	0.98	2.30
		−452	45.5	314	28.5	197	7.1	8	(c)	B	36.9	254	0.81	1.29
A444.0-F to 5456-H321	5556	RT	24.1	166	12.2	84	12.1	27	100	B	29.5	203	1.22	2.42
		−112	27.0	186	15.0	103	5.0	14	100	B	31.1	214	1.15	2.08
		−320	33.4	230	16.1	111	5.7	8	89	C	34.3	237	1.03	2.13
		−452	37.2	257	25.4	175	4.3	7	(c)	C	36.4	251	0.98	1.43
354.0-T62 to 354.0-T6	4043	RT	37.8	261	21.5	148	6.4	10	76	A	32.0	221	0.85	1.48
		−112	40.4	279	22.9	158	5.7	11	74	A	33.0	228	0.82	1.44
		−320	48.9	337	24.1	166	5.0	8	84	A	36.9	254	0.76	1.53
		−452	55.0	379	38.3	264	4.3	7	(c)	A	42.3	292	0.72	1.05
354.0-T62 to 6061-T6	4043	RT	30.8	212	19.0	131	9.3	39	62	C	28.7	198	0.93	1.51
		−112	35.8	247	21.8	150	7.1	7	66	A	31.5	217	0.88	1.44
		−320	43.1	297	23.0	159	5.0	7	71	A	34.7	239	0.81	1.51
		−452	45.9	317	35.7	246	2.9	4	(c)	A	37.4	258	0.82	1.05
354.0-T62 to 5456-H321	5556	RT	37.7	260	24.6	170	3.6	5	75	A	37.7	260	1.00	1.53
		−112	42.1	290	27.1	187	3.6	6	77	A	35.7	246	0.85	1.42
		−320	47.6	328	30.4	210	3.6	5	78	A	39.5	272	0.83	1.30
		−452	47.7	329	37.6	259	2.9	3	(c)	A	41.3	285	0.87	1.10
C355.0-T61 to 6061-T6	4043	RT	28.9	199	19.3	133	7.1	32	66	C	34.5	238	1.19	1.79
		−320	44.4	306	23.3	161	7.9	19	82	A	38.9	268	0.88	1.67
		−452	52.3	361	38.6	266	6.4	8	(c)	A	40.4	279	0.78	1.05
C355.0-T61 to 5456-H321	5556	RT	35.4	244	24.4	168	3.6	5	81	A	40.5	279	1.15	1.66
		−320	45.6	315	29.3	202	4.3	7	84	C	45.0	310	0.99	1.54
		−452	48.3	333	40.8	281	2.9	5	(c)	C	45.5	314	0.94	1.12

RT, room temperature; NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For joint yield strength, offset = 0.2%, over a 2 in. gage length. (b) Location of fracture of unnotched specimens; A, through weld; B, ½ to 2½ in. from weld; C, edge of weld. (c) No parent metal tests for comparison

Testing of High-Strength Metallic Materials (now ASTM Committee E-9) that about nineteen ASTM Standard Test Methods, including E 399 (Ref 27) were generated for the determination of fracture toughness parameters that relate the load-carrying capacity of structural members stressed in tension to the size of cracks, flaws, or design discontinuities that may be present in the stress field, shown in Fig. 8.22.

These parameters, primarily the stress-intensity factor, K, and the strain energy release rate, G, are more useful to the designer than those measures of toughness that provide only a relative merit rating of materials, such as notch tensile and tear tests. K and G characterize the potential fracture conditions in terms that permit structural designers to design resistance to unstable crack growth and catastrophic fracture into a structure, even with materials that are relatively low in toughness, including those sometimes described as brittle.

Since most castings are relatively thick and irregular in shape, this discussion focuses on the values of critical stress-intensity factor developed under plane-strain conditions, that is, in which plane sections remain plane, and stress buildup becomes three-dimensional in nature. This is appropriate not only because of the complex geometry of most castings, but also because it represents the most severe and, therefore, conservative situation. The critical value of plane-strain stress-intensity factors is referred to as K_{Ic}, and the remainder of the fracture toughness discussion for casting focuses on that value for individual casting alloys.

The limited applicability of linear elastic fracture mechanics to most aluminum alloys, that is, other than very-high-strength heat treated alloys, must be emphasized. Since the analysis is based on the assumption that unstable crack growth develops in elastically stressed material, the fracture toughness approach is applicable primarily to relatively high-strength materials with relatively low ductility. The type of brittle fracture behavior assumed in the development of linear-elastic fracture-mechanics concepts is seldom experienced with the majority of aluminum alloys, cast or wrought. Nevertheless, it is useful to overview the approach, provide representative data for those alloys for which the analysis is useful, and illustrate ways of estimating the fracture toughness of the tougher alloys.

What can be noted in summary is that fracture toughness data such as those in Table 8.23 for several aluminum casting alloys is that they may be used for the following purposes:

Alloy selection	By merit rating based on values of K_c and/or K_{Ic}
	By determination of residual load-carrying capacity with due regard for initial size of the discontinuity, the rate of fatigue crack propagation, and the design life of the structure
Design of new structures	Establish the design stress for a given component consistent with maximum expected crack length
	Establish limiting crack length for a component on the basis of a given operating stress
	Establish inspection criteria (including thoroughness and frequency) consistent with the potential initial crack size and the expected rate of fatigue crack propagation
Evaluation of existing structures	Estimate residual strength and tolerance for additional loading
	Estimate residual life consistent with observed crack length, rate of fatigue crack propagation, and critical crack length

It is important to recognize that values of "flaw" or "crack" size, as referred to above, must take into account any design discontinuities to which the real flaw or crack are adjacent or from which they grow. For example, a 3⁄16 in. (4.8 mm) hole, with a 1⁄8 in. (3.2 mm) fatigue crack growing out of one side constitutes a flaw 5⁄16 in. (8 mm) in length. In addition, in the case of castings, it must include the size of any internal porosity that serves as a crack initiator.

Of the aluminum casting alloys for which plane-strain fracture toughness data are available (Table 8.23), premium engineered castings of the 2xx.0 series consistently provided the highest values of K_{Ic}. For A201.0-T7, 224.0-T7, and 249.0-T7, K_{Ic} values were about or above 30 ksi$\sqrt{\text{in.}}$ (33 MPa$\sqrt{\text{m}}$).

The fracture toughness values are plotted as a function of tensile yield strength in Fig. 8.23.

While there is insufficient data to establish any meaningful trends, the superiority of premium engineered A201.0-T7 is even clearer in this presentation; it clearly has the best combination of strength and fracture toughness of this group of alloys. In fact, it is also apparent that there is a general superiority of all of the premium engineered 2xx.0 alloy castings over those of premium engineered 3xx.0 alloy castings with respect to their combination of strength and toughness. Sand cast 356.0-T6 exhibited the poorest performance in this respect, consistent with indicators from notch tensile and tear tests.

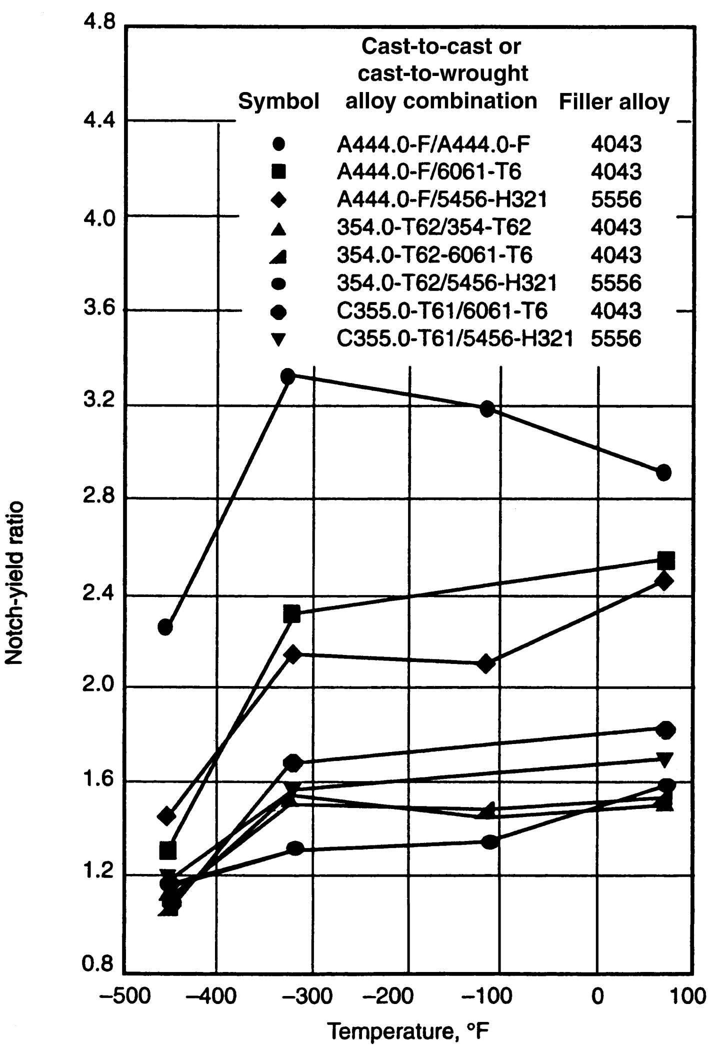

Fig. 8.16 Notch-yield ratio as a function of temperature for welds in aluminum alloy castings

8.5.4 Interrelation of Measures of Fracture Resistance

Based on analyses of thousands of data from tests of wrought alloys, there are fairly well defined and useful correlations between both NYR and UPE and the fracture toughness parameter K_{Ic} (Ref 24). For example, from data for wrought aluminum alloys, notch-yield ratio and unit propagation energy correlate well with K_{Ic} from the same lots of material as illustrated in Fig. 8.24 and 8.25, respectively.

These relationships are sufficiently well defined that in situations where K_{Ic} values have not been determined or where fully valid K_{Ic} values cannot be measured, the results of notch tensile and tear test results can be used to estimate plane-strain fracture toughness values.

Utilizing such correlations, it is possible to estimate the plane-strain fracture toughness of a few casting alloys for which sufficient NYR and UPE values are available, as illustrated in the far right columns of Table 8.24, where fracture parameters from the three tests are summarized. The estimated values are clearly identified, and that characterization should remain with them if/when they are taken out of this context for other use.

Caution must be exercised in the application of K_{Ic} values estimated in this manner; they are presented only to illustrate the range of K_{Ic} values that may be obtained from aluminum castings. This caution is particularly applicable for aluminum castings where individual cast components through their unique mold designs, metal flow characteristics, and chill procedures, may represent a wide range of fracture resistance. Ideally, once a fracture critical region is identified for a specific casting, a few fracture toughness tests would be made of specimens taken from those regions expected to experience the highest stresses.

8.6 Subcritical Crack Growth

As noted in Section 8.5.3, it is important when designing fracture critical structures to consider the case when a crack may initiate and grow as a result of service stresses, perhaps from an internal discontinuity of some type in the stress field. Discontinuities may be metallurgical in nature (e.g., forging defect or poros-

ity) or design based (e.g., rivet hole or window). For the analyses of such situations, it is appropriate to consider that whatever flaw or discontinuity cannot be ruled out reliably by nondestructive testing may well be present somewhere in the structure and may serve as the initiation site of fatigue crack growth that must be tracked.

Subcritical crack growth may occur during service loading by three mechanisms, fatigue, creep, and stress corrosion. Tests have been devised to define the resistance of materials to each of these three types of crack growth (Ref 24). Regrettably, there are relatively few data published on the subcritical crack growth of aluminum castings, but it is useful to see what can be gleaned from the available information.

Each of the three types of subcritical crack growth are examined in the following sections.

8.6.1 Fatigue Crack Growth

Fatigue crack growth rate (FCGR) data are conventionally measured by recording the rate of growth of a crack at the root of the notch in compact tension specimens of the type in Appendix 3, Fig. A3.7, and presenting the data in terms of the rate of crack growth as a function of the stress-intensity factor, K. As the crack grows longer, the stress intensity increases, and at some point potentially approaches the limiting critical conditions established from the fracture toughness tests (K_{Ic} or K_c) when complete fracture must be expected.

Fatigue crack growth tests may also be conducted in which the applied loads, and therefore stress intensities, are decreased gradually so that the limiting or "threshold" value of the applied K when growth no longer occurs may be measured.

The results of a programmed series of FCGR tests for A356.0-T6 castings produced by various methods, including conventional tilt (permanent) mold, squeeze cast, and vacuum high pressure (VRC/PRC) castings are presented in Fig. 8.26 and 8.27, for stress ratios of 0.1 and 0.5, respectively (Ref 18).

These figures illustrate that crack growth rates vary only slightly for the three casting processes, nor is there much difference in the threshold stress intensity levels for crack growth, as indicated by the data in Table 8.25.

Considering the scatter in the individual data from which the values in Table 8.25 are derived, it is difficult to conclude that the differences observed are significant. If there is any difference that may be worth investigating further, it is the advantage for the squeeze cast samples at 250 °F (120 °C).

Regrettably, such data are available for few casting alloys, and so once again it is useful to look at potentially useful correlations between more readily available test data and fatigue crack growth rates. Such a correlation has been noted between unit propagation energy from the tear test and fatigue crack growth rate for wrought aluminum alloys (Ref 24), as illustrated in Fig. 8.28; while no confirming test data are available for casting alloys, this relationship may be utilized to judge at least the relative ratings of cast alloys with respect to FCGR.

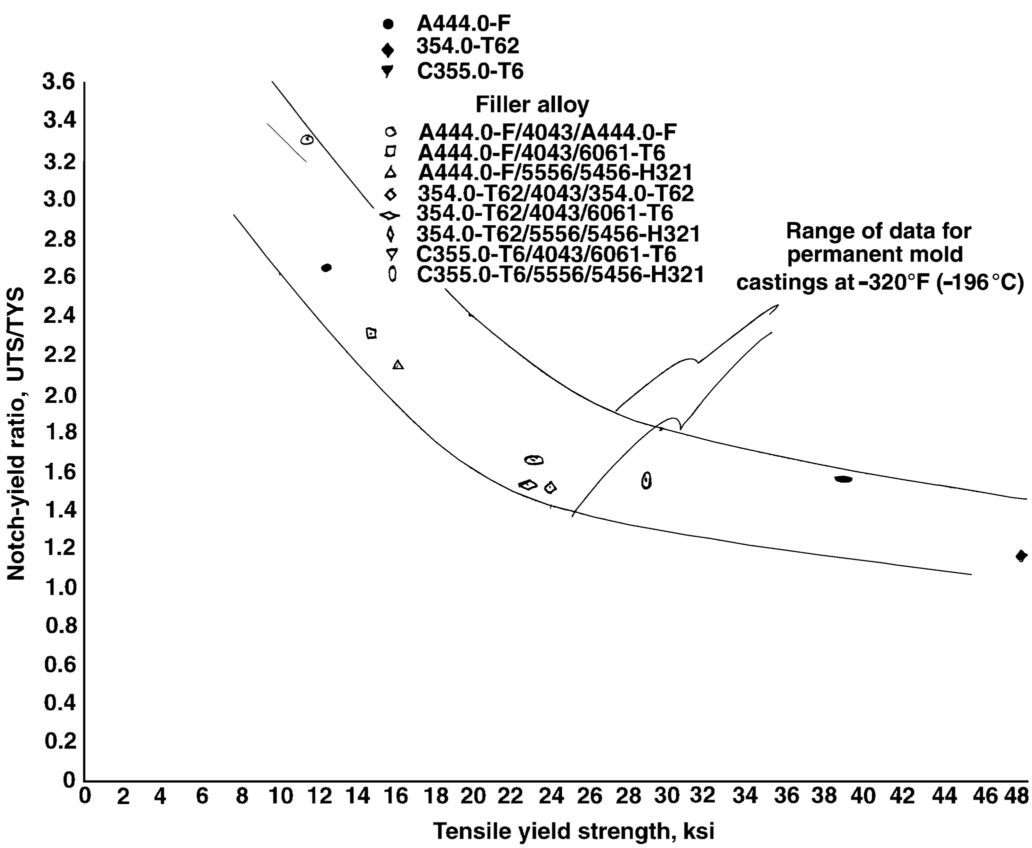

Fig. 8.17 Notch-yield ratio versus tensile yield strength for welded aluminum alloy castings at –320 °F (–196 °C) for combinations of casting alloys and filler alloys (middle number)

8.6.2 Creep Crack Growth

Evaluations of notched tensile and compact tension specimens under sustained loads have shown that some wrought aluminum alloys widely used in high-temperature applications (e.g., 2219) may experience some time-dependent crack growth at certain temperatures, referred to as creep crack growth (Ref 24). Such data are typically presented as in Fig. 8.29, which presents creep crack growth rates, *da/dt*, as a function of the applied stress-intensity factor, K_I. As in the case of fatigue crack growth rates, presentation in this format permits tracking of the crack growth in fracture-mechanics terms, relatable to the critical fracture conditions defined by fracture toughness tests.

Such data have not been developed to the authors' knowledge for cast aluminum alloys. However, it would be good design practice to at least consider this possibility when designing aluminum castings for sustained loads at high temperatures in the presence of severe stress raisers, including internal discontinuities. Corroborating tests may be worthwhile, and in this case it is useful to note that sustained load tests of severely notched tensile specimens have been shown to be good indicators of potential problems of this type.

8.6.3 Stress-Corrosion Crack Growth

For certain wrought 2xxx and 7xxx aluminum alloys—especially when subjected to stresses in the short-transverse (through-the-thickness) direction of thick plate, forgings, and extrusions—the potential for intergranular stress-corrosion crack growth must be considered. While this phenomenon has long been studied with tensile loading of smooth specimen subjected to exposure in potentially troublesome environments, it too can be examined in fracture mechanics terms of the rate of crack growth, *da/dt*, as a function of the applied stress-intensity factor, K_I.

Since most aluminum casting alloys, with notable exceptions, have not been found to be susceptible to stress-corrosion cracking (see Section 8.7), no such data have been developed for casting alloys and this phenomenon probably does not have to be addressed as a potential cause of subcritical crack propagation in most situations.

8.7 Corrosion Resistance

Rankings of the resistance of aluminum casting alloys to general corrosion and to stress-corrosion cracking are included in Table 8.26 (Ref 28). The solution potentials of a representative group of alloys are contained in Table 8.27.

A few specific comments about the corrosion resistance of specific alloy groups are also appropriate as presented below.

8.7.1 Aluminum-Copper Casting Alloys (2xx.x)

Alloys in which copper is the major alloying element are generally less resistant to corrosion than other alloy groups, and corrosion resistance tends to decrease with increasing copper content. This effect is attributed to the presence of minute galvanic cells created by the formation of copper-rich regions or films at the surface (28), which with increasing time, go into solution and replate onto the alloys to form metallic copper cathodes. Reduction of the copper ions and increased reaction of O^{2-} and H^+ increase the corrosion rate.

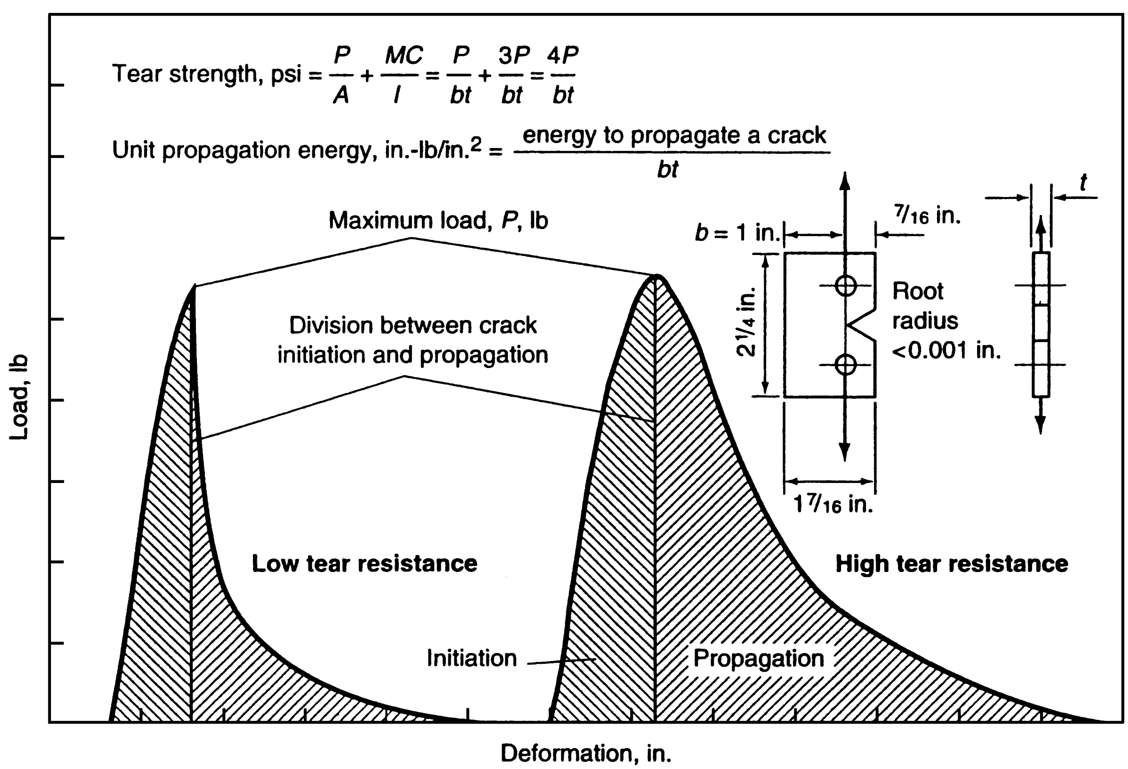

Fig. 8.18 Tear test specimen and representation of load-deformation curve from a tear test. A, area; M, moment; C, moment arm; I, moment of inertia

Table 8.21 Results of tensile and tear tests of aluminum alloy castings at room temperature

Specimens per Appendix 3, Fig. A3.6; each line represents average results of tests of duplicate specimens of one individual lot of material

Alloy and temper	Tensile tests: Ultimate tensile strength, ksi	Tensile tests: Ultimate tensile strength, MPa	Tensile tests: Tensile yield strength(a), ksi	Tensile tests: Tensile yield strength(a), MPa	Elongation in 2 in. %	Tear strength, ksi	Tear strength, MPa	TYR	Tear tests: Energy required to: initiate a crack, in.-lb	Tear tests: Energy required to: propagate a crack, in.-lb	Tear tests: Total energy, in.-lb	Tear tests: Unit propagation energy, in.-lb/in.^{2}	Tear tests: Unit propagation energy, mN · m/mm^2
Sand casting													
X335.0-T6	37.3	257	23.4	161	8.6	38.4	265	1.64	8	19	27	190	33
	35.3	243	22.6	156	6.8	39.3	271	1.74	11	19	30	195	34
Average	**35.4**	**244**	**22.9**	**158**	**7.7**	**38.8**	**268**	**1.69**	**10**	**19**	**29**	**192**	**34**
356.0-T4	31.1	214	19.8	137	4.4	32.8	226	1.66	7	19(b)	26(b)	190(b)	33(b)
	29.4	203	17.6	121	2.3	30.6	211	1.74	6	19(b)	25(b)	190(b)	33(b)
Average	**30.2**	**208**	**18.7**	**129**	**3.4**	**31.7**	**219**	**1.70**	**6**	**19(b)**	**26(b)**	**190(b)**	**33(b)**
356.0-T6	38.6	266	32.6	225	2.2	32.7	226	1.00	4	8	12	75	13
356.0-T7	37.8	261	33.7	232	1.6	39.2	270	0.87	3	7	10	70	12
356.0-T71	31.9	220	24.2	167	3.8	34.8	240	1.44	7	14	21	140	25
	29.4	203	20.7	143	4.1	32.2	222	1.55	7	11	18	110	19
	28.8	199	20.2	139	2.0	30.6	211	1.51	6	11	17	110	19
Average	**30.0**	**207**	**21.7**	**150**	**3.3**	**52.6**	**363**	**1.50**	**7**	**12**	**19**	**120**	**21**
A356.0-T7	37.1	256	30.5	210	4.4	34.2	236	1.12	5	8	13	75	13
	37.6	259	33.2	229	2.1	33.6	232	1.01	4	10	14	100	18
Average	**37.4**	**258**	**31.8**	**219**	**3.2**	**33.9**	**234**	**1.06**	**4**	**9**	**13**	**88**	**15**
B535.0-F	41.2	284	21.2	146	12.9	47.2	326	2.23	35	108	143	1075	188
	42.6	294	21.0	145	12.6	47.8	330	2.28	30	74	104	740	130
Average	**41.9**	**289**	**21.1**	**146**	**12.8**	**47.5**	**328**	**2.26**	**32**	**91**	**124**	**908**	**159**
Permanent mold casting													
X335.0-T61	40.8	281	28.4	196	8.5	43.2	298	1.52	9	22	31	220	39
	35.6	246	25.6	177	3.5	43.0	297	1.68	9	23	32	235	41
Average	**38.2**	**263**	**23.8**	**164**	**6.0**	**43.1**	**297**	**1.60**	**9**	**22**	**31**	**228**	**40**
354.0-T62	50.1	346	45.5	314	1.1	46.5	321	1.02	6	13	19	130	23
	47.8	330	44.3	306	0.9	45.9	317	1.04	6	13	19	125	22
Average	**49.0**	**340**	**44.9**	**310**	**1.0**	**46.2**	**319**	**1.03**	**6**	**13**	**19**	**128**	**22**
C355.0-T7	37.0	255	31.0	214	2.1	36.9	254	1.19	6	8	14	85	15
	41.0	283	30.4	210	2.5	33.2	229	1.04	4	8	12	75	13
Average	**39.0**	**269**	**30.7**	**212**	**2.3**	**35.0**	**241**	**1.12**	**5**	**8**	**13**	**80**	**14**
356.0-T6	35.8	247	31.1	214	1.4	40.6	280	1.30	8	10	18	105	18
	41.4	286	32.2	222	4.2	34.2	236	1.06	4	6	10	55	10
Average	**38.6**	**266**	**31.6**	**218**	**2.8**	**37.4**	**258**	**1.18**	**6**	**8**	**14**	**80**	**14**
356.0-T7	28.4	196	21.4	148	4.3	37.0	255	1.73	10	16	26	165	29
	31.7	219	22.6	156	7.5	38.3	264	1.70	10	17	27	170	30
	29.6	204	22.0	152	3.2	35.2	243	1.60	10	17	27	170	30
Average	**29.8**	**206**	**22.0**	**152**	**5.0**	**36.8**	**254**	**1.68**	**10**	**17**	**27**	**168**	**29**
A356.0-T61	39.4	272	30.8	212	4.3	43.2	298	1.40	9	14	23	140	25
	41.7	288	30.4	210	7.5	44.4	306	1.46	9	12	21	120	21
Average	**40.6**	**280**	**30.6**	**211**	**5.9**	**43.8**	**302**	**1.43**	**9**	**13**	**22**	**130**	**23**
A356.0-T62	40.9	282	36.7	253	2.1	46.2	319	1.26	9	14	23	145	25
	43.6	301	36.3	250	3.9	46.4	320	1.28	9	13	22	130	23
Average	**42.2**	**291**	**36.5**	**252**	**3.0**	**46.3**	**319**	**1.27**	**9**	**14**	**23**	**138**	**24**
A356.0-T7	28.2	194	21.4	148	5.3	29.8	206	1.86	14	30	44	295	52
	30.7	212	22.2	153	8.5	39.2	270	1.77	14	25	39	250	44
Average	**29.4**	**203**	**21.8**	**150**	**6.9**	**34.5**	**238**	**1.82**	**14**	**28**	**42**	**272**	**48**
359.0-T62	46.2	319	43.2	298	1.2	44.7	308	1.04	7	16	23	155	27
	47.4	327	43.1	297	1.6	41.0	283	0.95	4	12	16	115	20
Average	**46.7**	**322**	**43.2**	**298**	**1.4**	**42.8**	**295**	**1.00**	**6**	**14**	**20**	**135**	**24**
A444.0-F	23.2	160	9.7	67	22.2	27.6	190	2.85	19	39	58	390	68
	22.5	155	9.6	66	15.7	28.2	194	2.94	28	50	78	495	87
Average	**22.8**	**157**	**9.6**	**66**	**19.0**	**27.9**	**192**	**2.90**	**24**	**44**	**68**	**442**	**77**
A444.0-T4	23.0	159	8.0	55	24.4	27.1	187	3.39	30	57	107	580	102
Premium engineered castings													
C355.0-T61	43.6	301	30.3	209	6.4	51.8	357	1.71	14	28	40	275	48
A356.0-T6	41.6	287	30.2	208	8.8	51.6	356	1.71	18	34	52	345	60
A357.0-T61	51.2	353	40.0	276	11.4	54.2	374	1.35	10	19	29	190	33
A357.0-T62	53.9	372	46.4	320	5.3	53.8	371	1.16	11	12	23	125	22

TYR, tear strength to yield strength ratio. (a) For yield strength, offset = 0.2%. (b) Estimated; tear energy curve not well defined

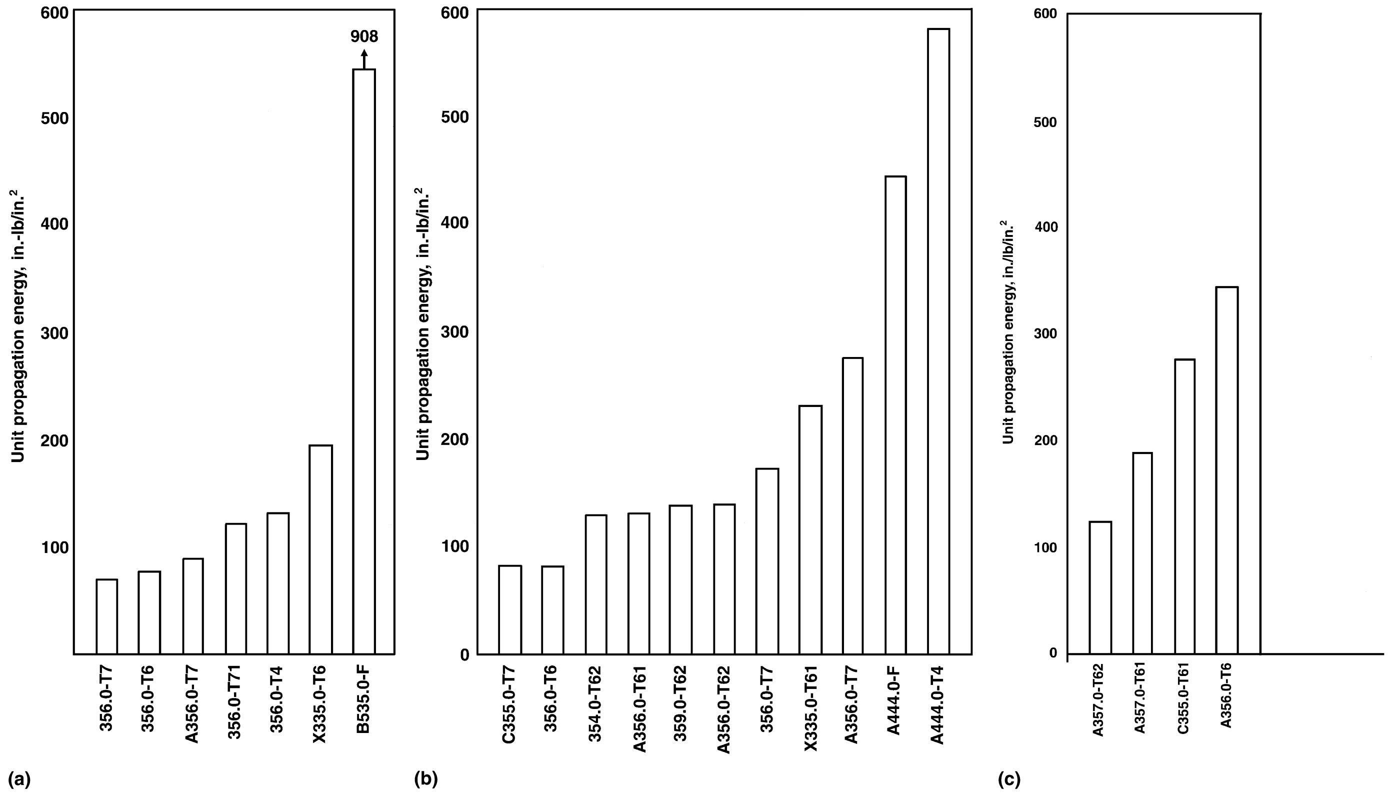

Fig. 8.19 Ratings of aluminum alloy castings based on unit propagation energy from tear tests. (a) Sand castings. (b) Permanent mold castings. (c) Premium engineered castings

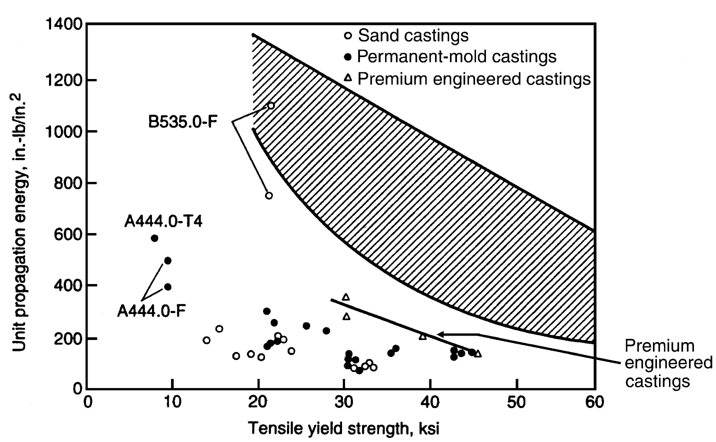

Fig. 8.20 Unit propagation energy versus tensile yield strength for aluminum alloy castings

Table 8.22 Representative tear and tensile tests results of groove welds in cast-to-cast and cast-to-wrought aluminum alloys at room temperature

Specimens per Appendix 3, Fig. A3.6; each line represents average results of tests of duplicate specimens for one individual lot of material. Joint yield strength not determined; ratio of tear strength to yield strength not available. No postweld thermal treatment.

Alloy and temper combination	Filler alloy	Tensile tests: Reduced section tensile strength, ksi	Tensile tests: Reduced section tensile strength, MPa	Tensile tests: Free bend elongation, %	Tensile tests: Tear specimen type (Fig. A3.6)	Tear tests: Tear strength, ksi	Tear tests: Tear strength, MPa	Tear tests: Energy required to: initiate a crack, in.-lb	Tear tests: Energy required to: propagate a crack, in.-lb	Tear tests: Total energy, in.-lb	Unit propagation energy, in.-lb/in.^{2}	Unit propagation energy, mN · m/mm^2
Sand casting												
A444.0-F to A444.0-F	5556	37.8	261	18.8	A	51.0	352	60	103	163	1030	180
					B	46.9	323	38	82	120	820	144
					C	50.6	349	64	94	158	935	164
A444.0-F to 6061-T6	5556	32.5	224	12.2	A	49.5	341	56	105	161	1050	184
					B	45.0	310	32	77	109	770	135
					C	47.7	329	46	92	138	920	161
A444.0-F to 5456-H321	5556	42.6	294	12.2	A	53.0	366	66	115	181	1185	208
					B	49.6	342	38	91	129	910	159
					C	50.1	346	61	99	160	990	173
356.0 to 6063-T4	4043	28.5	197	4.1	A	26.9	186	3	16	19	160	28
					B	37.4	258	11	24	34	240	42
					C	34.2	236	6	32	38	325	57
356.0-T6 to 6061-T6	5556	28.4	196	2.0	A	29.6	204	6	15	21	150	26
					B	34.4	237	9	21	30	210	37
					C	31.8	219	9	18	27	185	32
	4043	27.0	186	6.9	A	30.3	209	7	16	23	175	31
					B	34.4	237	10	31	41	310	54
					C	25.7	177	6	33	39	330	58
356.0-T7 to 6061-T6	5556	26.8	185	4.6	A	30.0	207	7	14	21	145	25
					B	34.2	236	12	20	32	205	36
					C	30.0	207	8	32	40	320	56
	4043	25.8	178	7.2	A	29.7	205	6	22	28	220	39
					B	32.8	226	11	30	41	295	52
					C	26.6	183	8	38	46	380	67
356.0-T71 to 356.0-T71	4043	26.5	183	6.1	A	28.8	199	8	18	26	175	31
					B	32.4	223	14	32	46	320	56
					C	27.8	192	8	24	32	245	43
356.0-T71 to 6061-T6	4043	26.7	184	9.4	A	29.4	203	8	20	28	205	36
					B	33.4	230	15	30	45	305	53
					C	27.6	190	9	44	53	435	76
356.0-T71 to 5456-H321	4043	25.7	177	5.7	A	30.8	212	8	14	22	140	25
					B	32.8	226	8	18	26	185	32
					C	29.6	204	11	16	27	165	29
A357.0-T7 to 6061-T6	5556	25.9	179	8.2	A	51.2	353	61	112	173	1120	196
					B	50.3	347	42	100	142	995	174
					C	50.2	346	60	101	161	1010	177
Permanent mold casting												
C355.0-T7 to 6061-T6	4043	32.0	221	16.6	A	36.4	251	12	45	57	445	78
					B	35.1	242	10	28	38	275	48
					C	40.0	276	14	30	44	305	53
356.0-T6 to 356.0-T6	4043	28.1	194	11.4	A	34.0	234	14	34	48	340	60
					B	32.8	226	13	34	47	340	60
					C	32.7	226	11	26	37	265	46
356.0-T6 to 6061-T6	4043	28.8	199	12.5	A	35.2	243	13	46	59	455	80
					B	34.2	236	11	29	40	290	51
					C	33.6	232	10	28	38	275	48
356.0-T6 to 5456-H321	4043	29.5	203	14.3	A	39.4	272	28	41	71	410	72
					B	32.7	226	6	18	24	175	31
					C	39.4	272	17	42	59	420	74
356.0-T7 to 356.0-T7	4043	25.6	177	8.2	A	34.2	236	22	31	53	310	54
					B	31.8	219	14	33	47	330	58
					C	31.0	214	13	36	49	365	64
356.0-T7 to 6061-T6	4043	27.6	190	9.8	A	38.2	263	27	38	65	375	66
					B	34.3	237	15	36	51	355	62
					C	43.6	301	34	70	104	700	123

(continued)

Table 8.22 (continued)

Alloy and temper combination	Filler alloy	Tensile tests: Reduced section tensile strength, ksi	Reduced section tensile strength, MPa	Free bend elongation, %	Tear specimen type (Fig. A3.6)	Tear strength, ksi	Tear strength, MPa	Tear tests: Energy required to: initiate a crack, in.-lb	propagate a crack, in.-lb	Total energy, in.-lb	Unit propagation energy, in.-lb/in.^{2}	Unit propagation energy, mN · m/mm^2
Permanent mold casting (continued)												
356.0-T7 to 5456-H321	4043	26.6	183	4.0	A	37.4	258	38	30	68	295	52
					B	24.3	168	2	10	12	105	18
					C	33.0	228	13	31	44	310	54
A356.0-T61 to 6061-T6	4043	28.6	197	9.8	A	36.8	254	25	50	75	495	87
					B	33.4	230	10	35	45	350	61
					C	35.2	243	14	42	56	415	73
A356.0-T62 to 6061-T6	4043	26.7	184	10.5	A	37.6	259	32	48	70	475	83
					B	34.2	236	15	36	51	365	64
					C	37.8	261	20	52	72	520	91
A356.0-T7 to 6061-T6	4043	25.2	174	11.8	A	39.0	269	37	41	78	410	72
					B	34.0	234	16	40	56	395	69
					C	33.6	232	11	27	38	270	47

The undesirable corrosion effects of copper in aluminum can be minimized with good heat treating and quenching practices. A high rate of quench and sufficient artificial aging will be beneficial (Ref 28).

Some aluminum-copper alloys in the T4 and underaged conditions are among the most susceptible known to stress-corrosion failure.

8.7.2 Al-Si-Cu and/or Mg Casting Alloys (3xx.x)

While elemental silicon is present in the 3xx.x series alloys, and silicon is cathodic to the aluminum matrix, the effects of silicon on corrosion resistance are minimal because the silicon particles are highly polarized and the resultant current density is low.

The corrosion resistance of the 3xx.x series, as of the 2xx.x series, is closely related to the copper content and also to impurity levels. Modifications of several of the basic alloy compositions to restrict impurity levels have benefited corrosion resistance as well as certain mechanical properties including toughness.

8.7.3 Aluminum-Silicon Casting Alloys (4xx.x)

As noted for the 3xx.x alloys, the effects of silicon on the corrosion resistance of aluminum casting alloys are minimal, and this group as a whole has relatively good corrosion resistance.

8.7.4 Aluminum-Magnesium Casting Alloys (5xx.x)

Aluminum-magnesium casting alloys have excellent resistance to corrosion and are resistant to a wide range of chemical and food products, making them especially useful in these industries and in marine applications.

8.7.5 Aluminum-Zinc Casting Alloys (7xx.x)

Aluminum-zinc alloys, because of their zinc contents, are anodic to most other aluminum casting alloys and have generally good corrosion resistance. They are better than the 2xx.x series for general corrosion resistance, but inferior to the 5xx.x series.

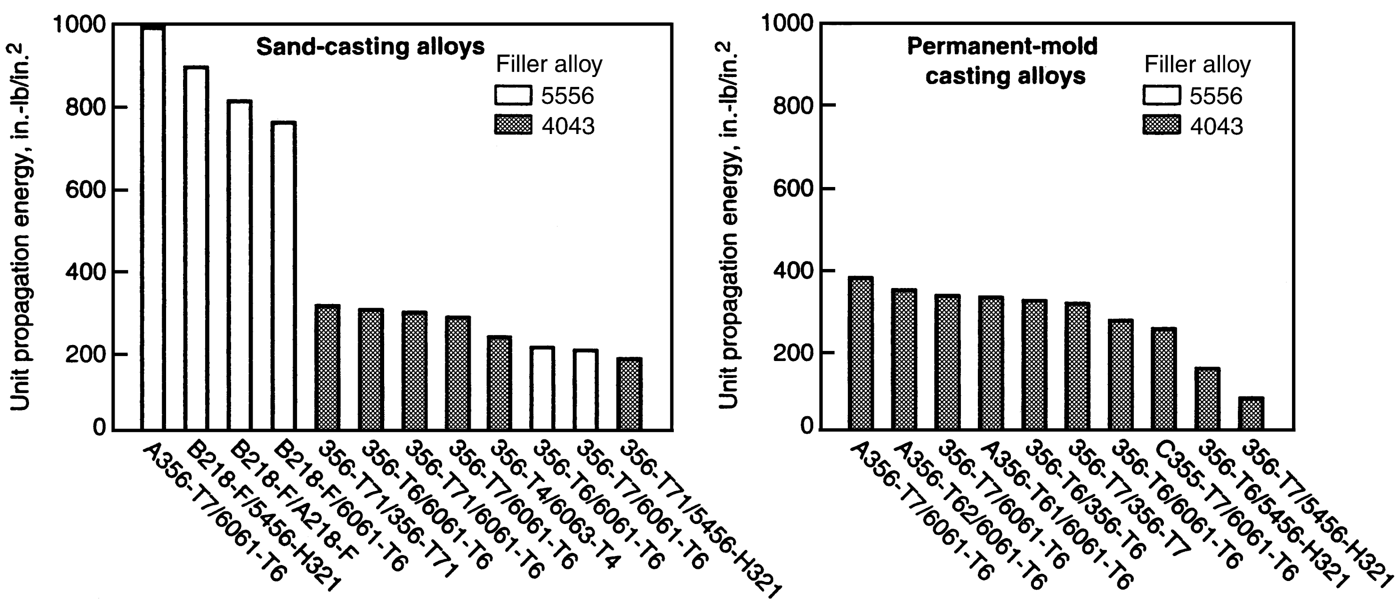

Fig. 8.21 Ratings of welds in aluminum castings based on unit propagation energy from tear tests

Table 8.23 Results of plane strain fracture toughness tests of representative aluminum alloy premium engineered castings

Individual results of single cast slabs from which specimens were machined; tests in accordance with ASTM Method E 399 at time tests were made to. Specimens generally machined from two different directions in casting; fracture results were averaged independent of direction.

		Tensile tests					Plane-strain fracture toughness tests												
Alloy and temper	Testing direction(a)	Ultimate tensile strength, ksi	Ultimate tensile strength, MPa	Tensile yield strength, ksi	Tensile yield strength, MPa	Elongation in 2 in., %	Type of specimen(b)	Specimen thickness (B), in. (mm)	Specimen width (W), in. (mm)	Crack length (a_o), in. (mm)	Ratio a_o/W	Critical load P_o, kips (N)	Maximum load P_{max}	Ratio P_{max}/P_o	Plane-strain fracture toughness, (K_{Ic}), ksi · in.$^{1/2}$	Plane-strain fracture toughness, (K_{Ic}), MPa · m$^{1/2}$	Valid measure of K_{Ic} (c)	Critical crack-size index(d), in.	Critical crack-size index(d), mm
Sand casting																			
356.0-T7	L	37.8	261	33.7	232	1.6	CC	0.375	1.500	0.500	0.33	13.00	13.80	1.06	15.4	16.9	Yes	0.21	5.3
Premium engineered casting																			
A201.0-T7	L	63.3	437	57.4	396	7.0	CT	1.25 (31.8)	2.50 (63.5)	1.38 (35.1)	0.55	5.85	6.49	1.11	33.8	37.2	Yes	0.35	8.8
										1.35 (34.3)	0.54	6.00	. . .	1.00	32.9	36.2	Yes	0.33	8.3
	T	64.2	443	58.8	406	7.0	CT	1.25 (31.8)	2.50 (63.5)	1.37 (34.8)	0.55	6.12	6.60	1.08	34.5	38.0	Yes	0.34	8.7
										1.35 (34.3)	0.54	6.00	6.46	1.08	33.1	36.4	Yes	0.32	8.0
															33.6	37.0	Yes	0.34	8.6
224.0-T7	L	53.3	368	39.6	273	6.8	CT	1.25 (31.8)	2.50 (63.5)	1.40 (35.6)	0.56	4.60	7.44	1.62	27.2	29.9	No(e)	0.47	12.0
										1.40 (35.6)	0.56	5.44	7.40	1.36	31.8	35.0	No	0.64	16.4
	T	54.9	379	42.5	293	6.5	CT	1.25 (31.8)	2.50 (63.6)	1.38 (35.1)	0.55	5.00	7.02	1.40	28.6	31.5	No	0.45	11.5
										1.38 (35.1)	0.55	5.81	7.58	1.30	33.1	36.4	No	0.61	15.4
															30.2	33.2	No	0.54	13.7
249.0-T7	L	56.8	392	47.6	328	7.2	CT	1.25 (31.8)	2.50 (63.5)	1.37 (34.8)	0.55	5.38	5.82	1.08	30.2	33.2	Yes	0.40	10.2
										1.39 (35.3)	0.55	5.02	5.35	1.06	29.1	32.0	Yes	0.37	9.5
	T	58.3	402	50.9	351	7.5	CT	1.25 (31.8)	2.50 (63.5)	1.37 (34.8)	0.55	5.40	6.10	1.13	30.4	33.4	Yes	0.36	9.1
										1.34 (34.0)	0.53	5.38	5.80	1.08	29.1	32.0	Yes	0.33	8.3
															29.7	32.7	Yes	0.36	9.1
354.0-T6	L	48.4	334	43.0	297	1.5	CT	1.25 (31.8)	2.50 (63.5)	1.34 (34.0)	0.54	3.40	3.50	1.03	18.5	20.4	Yes	0.19	4.7
										1.31 (33.3)	0.52	3.44	3.50	1.02	18.0	19.8	Yes	0.18	4.5
	T	47.6	328	42.9	296	1.0	CT	1.25 (31.8)	2.50 (63.5)	1.24 (31.5)	0.50	3.65	3.72	1.02	17.5	19.3	Yes	0.17	4.2
										1.27 (32.3)	0.51	3.68	3.88	1.05	18.2	20.0	Yes	0.18	4.6
															18.0	19.8	Yes	0.18	4.6
C355.0-T6	L	44.2	305	40.7	281	1.5	CT	1.25 (31.6)	2.50 (63.5)	1.27 (32.3)	0.51	3.68	4.08	1.11	18.3	20.1	Yes	0.20	5.1
										1.32 (33.5)	0.53	3.46	3.80	1.10	18.3	20.1	Yes	0.20	5.1
	T	43.0	297	41.0	283	<0.5	CT	1.25 (31.8)	2.50 (63.5)	1.25 (31.8)	0.50	3.81	4.12	1.08	18.6	20.5	Yes	0.21	5.2
										1.31 (33.3)	0.52	3.70	3.98	1.07	19.3	21.2	Yes	0.22	5.6
															18.7	20.6	Yes	0.21	5.3
A357.0-T62	L	50.2	346	43.2	298	2.5	CT	0.75 (19.0)	1.50 (38.1)	0.73 (18.5)	0.48	1.83	2.00	1.04	19.3	21.2	Yes	0.20	5.1
										0.78 (19.8)	0.52	1.88	1.92	1.02	21.0	23.1	Yes	0.24	6.0
	T	53.7	370	43.3	299	6.5	CT	0.75 (19.0)	1.50 (38.1)	0.74 (18.8)	0.50	1.90	1.98	1.04	19.6	23.6	Yes	0.20	5.2
										0.68 (17.3)	0.45	1.82	1.93	1.06	19.2	21.1	No	. . .	. . .
															20.5	22.6	Yes	0.21	5.3

(a) L, longitudinal; T, transverse. (b) CC, center-cracked specimens; CT, compact tension specimens (Appendix 3, Fig. A3.7); all specimens were precracked by fatigue. (c) Based on criteria in ASTM E 399 at time tests were made. (d) A relative measure of crack tolerance of material, defined as $(K_{Ic}/TYS)^2$. (e) P_{max}/PQ ratio too high

Many wrought aluminum-zinc alloys of the comparable 7xxx series are susceptible to stress-corrosion cracking (SCC) under short-transverse stressing and require special aging treatments for added protection; this is less of a concern in castings where grain deformation is not present. Nevertheless, some in-service failures have been observed in certain alloys such as 707.0-T5 and 771.0-T5, and some caution is advised to avoid conditions that may lead to intergranular attack.

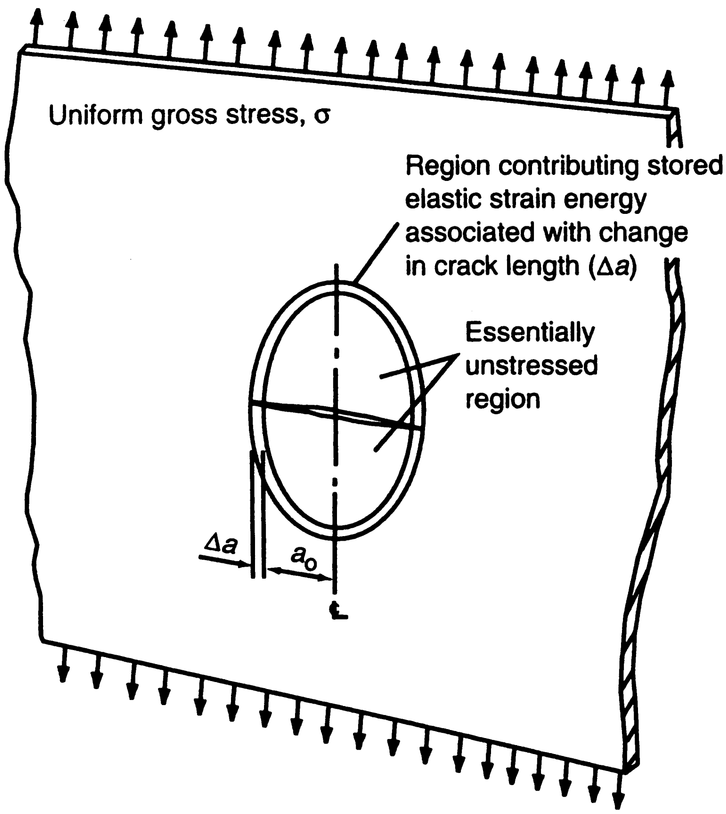

Fig. 8.22 Large elastically stressed panel containing a crack

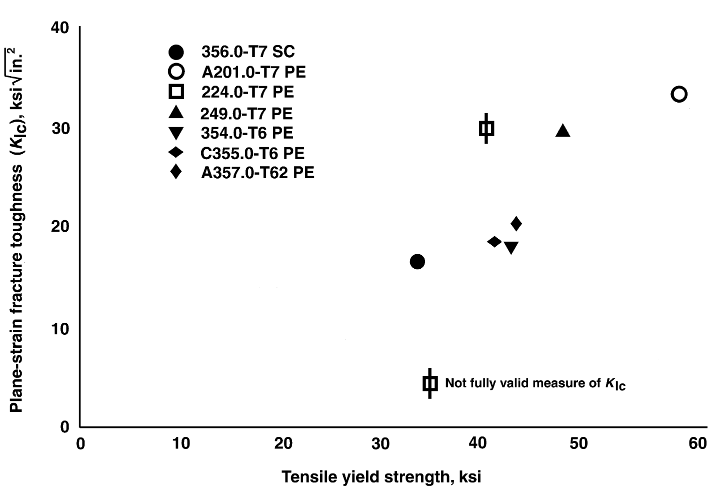

Fig. 8.23 Plane-strain fracture toughness, K_{Ic}, versus tensile yield strength for selected aluminum alloy castings. SC, sand cast alloy; PE, premium engineered alloy

8.7.6 *Aluminum-Tin Casting Alloys (8xx.x)*

Tin in aluminum castings is cathodic to the aluminum matrix and results in some decrease in general corrosion resistance in aqueous saline solutions. These alloys are quite successfully used in other environments.

8.8 Properties of Cast Aluminum Matrix Composites

Cast aluminum matrix composites (AlMMCs) are discussed separately because less information is available in the way of typical and statistical minimum mechanical and physical properties for these products. For this reason, the authors recommend that these products be used cautiously and with the understanding that the appropriate design mechanical properties for specific products may

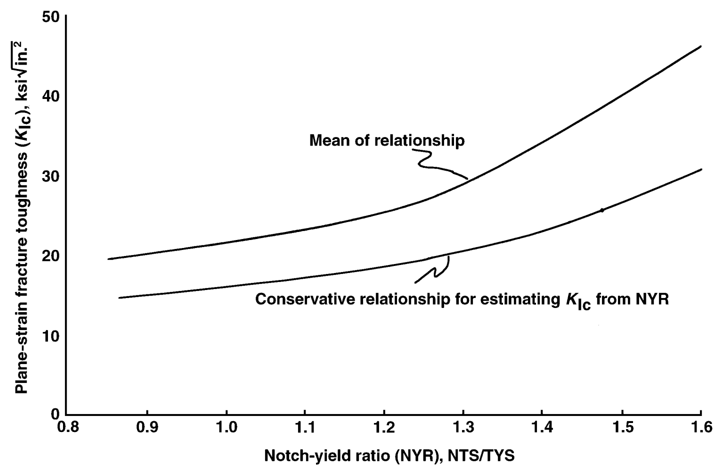

Fig. 8.24 Plane-strain fracture toughness, K_{Ic}, versus notch-yield ratio for some cast aluminum alloys compared to the mean values of the relationship for wrought aluminum alloys

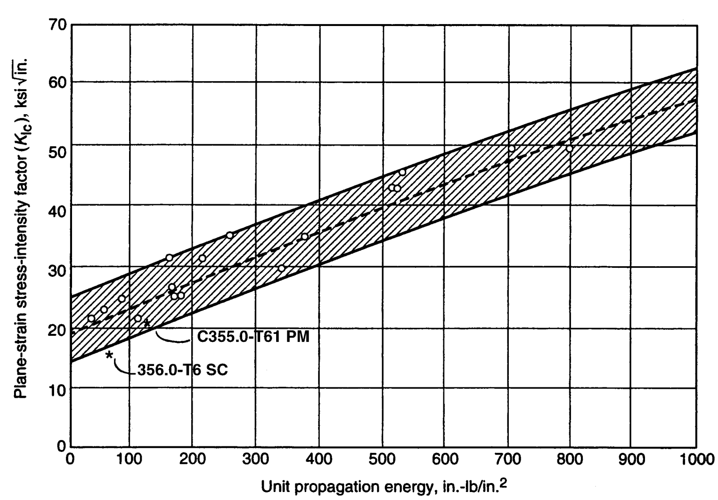

Fig. 8.25 Plane-strain fracture toughness, K_{Ic}, versus notch-yield ratio for selected cast aluminum alloys compared to the range of such values for wrought aluminum alloys. SC, sand cast; PM, permanent mold

Table 8.24 Summary of rounded average fracture parameters for representative aluminum casting alloys

Average values taken from previous tables as footnoted. Values averaged when data for multiple lots are available.

Alloy and temper	Tensile yield strength		Elongation in 2 in.,	Notch-yield	Unit propagation energy(b)		Measured plane-strain fracture toughness (K_{Ic})(c)		Conservative estimated plane-strain fracture toughness (K_{Ic})(d)		Estimated relative critical crack-size index(c)	
	ksi	MPa	%	ratio(a)	in. · lb/in.^{2}	mN · m/mm2	ksi · in.$^{1/2}$	MPa · m$^{1/2}$	ksi · in.$^{1/2}$	MPa · in.$^{1/2}$	in.	mm
Sand casting												
240.0-F	26.0	179	1.4	0.87	...	...	...	...	16	18	0.62	16
242.0.F	20.4	141	2.1	1.34	...	...	...	...	21	23	1.03	26
295.0-T6	27.1	187	6.4	1.75	...	...	...	...	>35	>38	>1.67	>42
308.0-F	18.5	128	1.8	1.19	...	...	...	...	19	21	1.03	26
X335.0-T6	22.9	158	7.7	1.64	192	34	...	...	26	29	1.14	29
356.0-T4	18.7	129	3.4	1.69	128	22	...	...	19	21	1.02	26
356.0-T6	32.6	225	2.2	1.15	75	13	...	...	18	20	0.55	14
356.0-T7	33.7	232	1.6	1.02	70	12	15.4(f)	16.9(f)	...	...	0.21(f)	5.3(f)
356.0-T71	21.7	150	3.3	1.54	120	21	...	...	23	25	1.06	27
A356.0-T6	30.2	208	8.8	1.70	...	...	...	...	>35	>38	>1.34	>34
A356.0-T7	31.8	219	3.2	1.31	88	15	...	...	21	23	0.66	17
520.0-T4	31.6	218	2.1	1.22	...	...	...	...	20	22	0.63	16
B535.0-F	21.1	146	12.8	2.10	908	159	...	...	>50	>55	>5.6	>142
A612.0-F	34.8	240	3.2	1.31	...	...	...	...	21	23	0.60	15
Permanent mold casting												
X335.0-T61	23.8	164	6.0	1.60	228	40	...	...	28	31	1.18	30
354.0-T62	44.9	310	1.0	1.18	128	22	...	...	22	24	0.49	12
C335.0-T7	30.7	212	2.3	1.39	80	14	...	...	20	22	0.65	17
356.0-T6	31.6	218	2.8	1.36	80	14	...	...	23	25	0.73	18
356.0-T7	22.0	152	5.0	1.60	168	29	...	...	30	33	1.36	35
A356.0-T61	30.6	211	5.9	1.65	130	23	...	...	25	28	0.82	21
A356.0-T62	35.5	245	3.0	1.24	138	24	...	...	22	24	0.62	16
A356.0-T7	21.8	150	6.9	1.72	272	48	...	...	30	33	1.38	35
359.0-T62	43.2	298	1.4	1.08	135	24	...	...	19	21	0.44	11
A444.0-F	9.6	66	19.0	2.96	442	77	...	...	>50	>55	>27	>690
A444.0-T4	8.0	55	24.4	3.72	580	102	...	...	>50	>55	>39	>1000
Premium engineered casting												
A201.0-T7	58.1	401	7.0	1.38	...	...	33.6	37.0	...	...	0.34	8.6
224.0-T7	41.4	286	6.6	1.60	...	...	30.2	33.2	...	...	0.54	13.7
249.0-T7	49.2	339	7.4	1.40	...	...	29.7	32.7	...	...	0.36	9.1
354.0-T6	43.0	297	1.2	1.01	...	...	18.0	19.8	...	...	0.18	4.6
C355.0-T6	40.8	281	1.0	1.07	...	...	18.6	20.6	...	...	0.21	5.31
C355.0-T61	30.3	209	6.4	1.74	275	48	...	...	30	33	0.99	25
A356.0-T6	30.2	208	8.8	1.70	345	60	...	...	>35	>38	>1.67	>42
A357.0-T6	43.2	298	4.5	1.12	...	...	...	...	18	20	0.42	11
A357.0-T61	40.0	276	11.4	1.44	190	33	...	...	25	28	0.63	16
A357.0-T62	44.7	308	5.8	1.28	125	22	19.8	20.8	...	...	0.2	5.0

(a) Values from Table 8.17. (b) Values from Table 8.21. (c) Values from Table 8.23, fully valid except as noted in (f). (d) Square of ratio K_{Ic}/TYS, a relative measure of critical crack size tolerance. (e) For those alloys and tempers for which fracture toughness tests were not made; estimated conservatively from notch-tensile and tear test results based on correlations. (f) Invalid test because of high P_{max}/PQ value; must be considered an estimate

have to be developed with additional testing at the time of their proposed application.

Typical values of several AlMMCs published by NADCA and several producers are presented in Table 8.28, their typical physical properties in Table 8.29, and their performance characteristics in Table 8.30 (Ref 28–30).

As noted in these tables, among the information provided are data for two cast aluminum matrix alloys, 301.0 and 303.0, each containing two different percentages of silicon carbide (SiC) particulate, 10% and 20%. Attention is called to the fact that these composites are referred to by some sources in the literature with designations consistent neither with the Aluminum Association registration records nor with the ANSI Standard for MMC nomenclature. The correct designations based on the compositions given in Ref 6, 301.0 and 303.0, are presented in Tables 8.28 through 8.30, with footnotes to the published designations. Similarly, data for matrix alloy 361.0 are presented with the appropriate Aluminum Association designation, not the designation under which the products were produced, also as footnoted in the tables.

The most significant differences between the properties of the composites and those of the matrix alloys are the elastic moduli: for the composites, the moduli are 50 to 100% higher than those of the matrix alloys, depending on the percentage of SiC particulate included. The SiC particulate, with its own modulus near 100 $\times 10^6$ psi (700 GPa), contributes materially to the stiffness of the finished product. The higher moduli are the principal reason for the production and application of aluminum metal matrix composites.

Among the other advantages of the composites that have proven important in commercial applications are the lower coefficients of thermal expansion (CTE) and the higher thermal conductivity. In particular, the lower CTEs better match those of some of the materials with which they are used (in applications such as sinks in satellite electronics), resulting in lower local stresses and minimizing the risk of thermal fatigue failure.

Aluminum MMCs also have superior fatigue properties in comparison to unreinforced aluminum alloys, as illustrated by Fig. 8.30. With reinforcement, the fatigue strengths at specific lives are

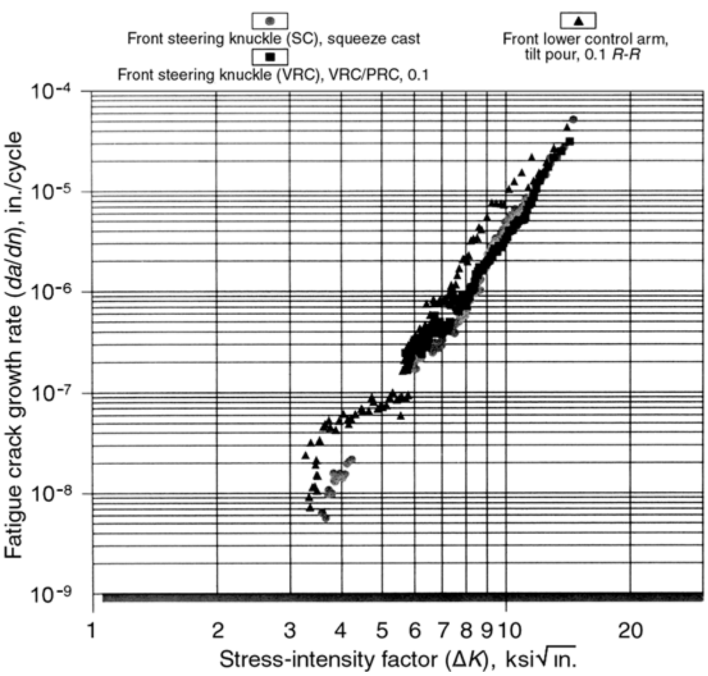

Fig. 8.26 Fatigue crack growth rate (R = 0.1) versus stress-intensity factor at room temperature for A356.0-T6 aluminum alloy castings produced by various processes

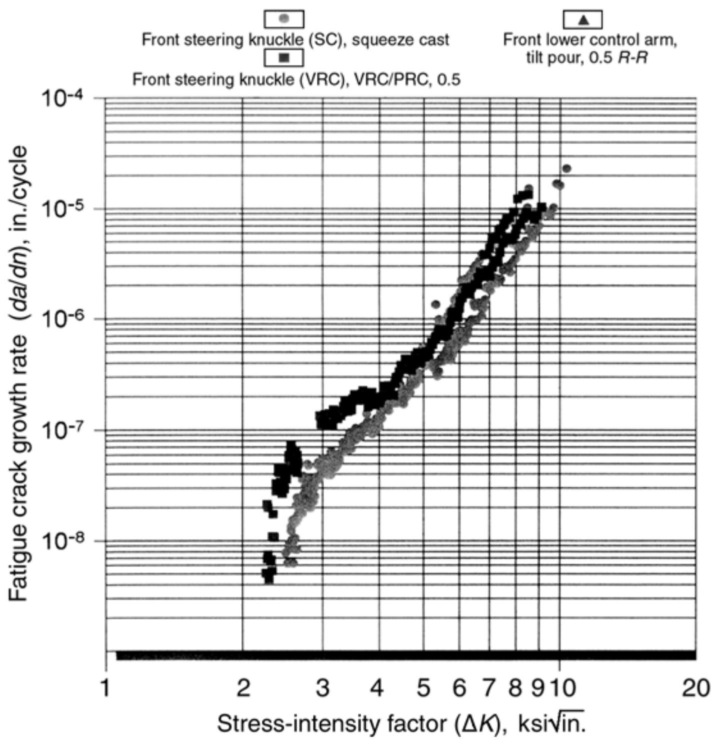

Fig. 8.27 Fatigue crack growth rate (R = 0.5) versus stress-intensity factor at room temperature for A356.0-T6 aluminum alloy castings produced by various processes

Table 8.25 Threshold stress intensities for fatigue crack propagation for alloy A356.0-T6

Casting process	Threshold stress intensity at room temperature				Threshold stress intensity at 250 °F (120 °C)			
	R = 0.1		*R* = 0.5		*R* = 0.1		*R* = 0.5	
	ksi$\sqrt{\text{in.}^2}$	MPa$\sqrt{\text{m}^2}$	ksi$\sqrt{\text{in.}^2}$	MPa$\sqrt{\text{m}^2}$	ksi$\sqrt{\text{in.}^2}$	MPa$\sqrt{\text{m}^2}$	ksi$\sqrt{\text{in.}^2}$	MPa$\sqrt{\text{m}^2}$
Tilt mold (PM)	3.41	3.75	2.35	2.58	3.92	4.31	2.4	2.64
Squeeze	3.32	3.65	2.78	3.05	4.17	4.58	3.14	3.45
Vacuum	3.84	4.22	2.37	2.60	3.18	3.49	2.37	2.60

PM, permanent mold. *R*, fatigue stress ratio, the ratio of the minimum stress to the maximum stress in each cycle of loading. Source: Ref 18

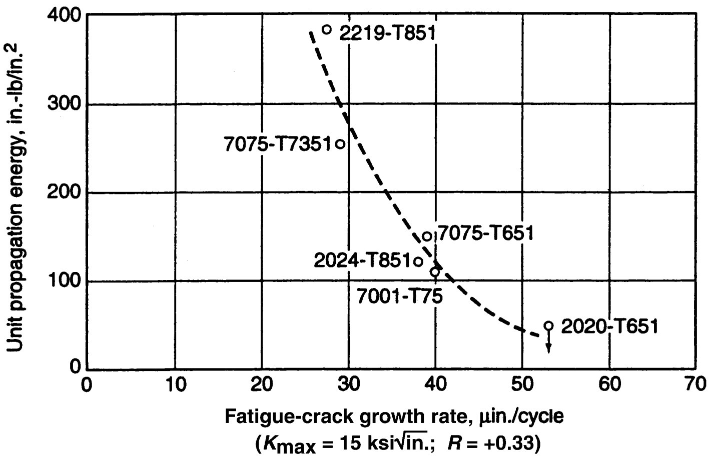

Fig. 8.28 Relationship between unit propagation energy from the tear test and fatigue crack growth rate for wrought aluminum alloys. K_{max} = 15 ksi$\sqrt{\text{in.}}$; R = 0.33.

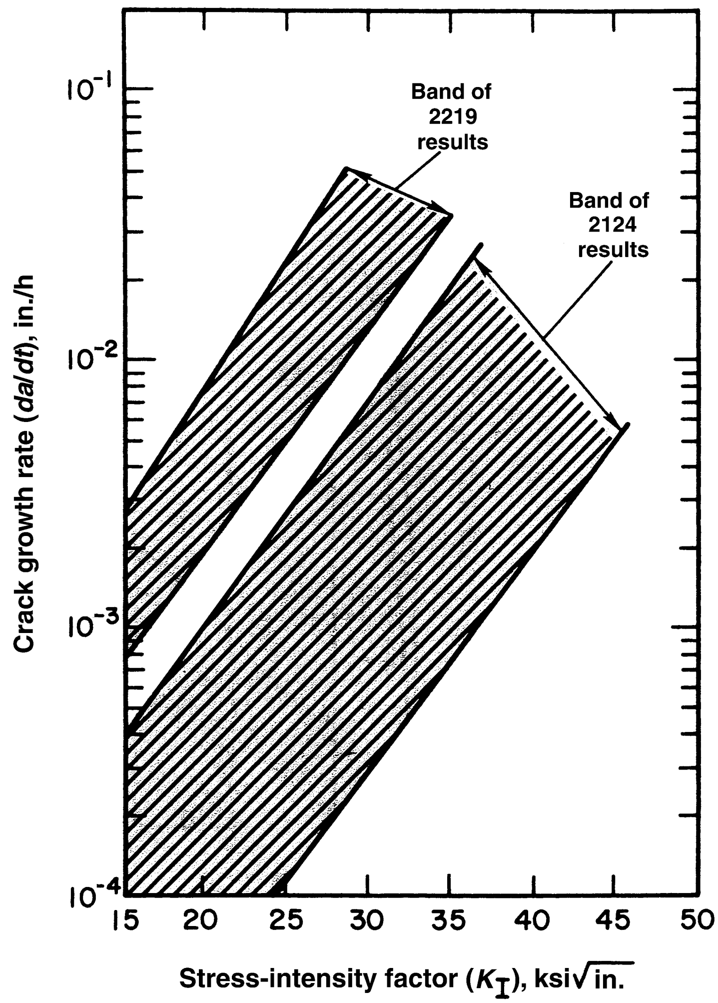

Fig. 8.29 Creep crack growth as a function of applied stress-intensity factor for selected wrought aluminum alloys

20 to 50% higher, with the endurance limit (10^7 cycles) indicated as nearly twice the value as for unreinforced material.

Finally, there appears to be an added advantage in higher damping capacity for aluminum MMCs versus unreinforced alloys, although this is difficult to demonstrate quantitatively. As illustrated in the decay curves in Fig. 8.31, externally induced vibrations decay relatively quickly in the aluminum MMC as compared with those in conventional aluminum alloy 5052 and other structural alloys.

It is important to note (from Table 8.28) that the benefits of higher moduli and fatigue strength, plus lower CTE, bring some trade-off in substantially lower elongation and fracture toughness than those of the matrix alloys. This is supported by the fact that in the cases where such data are presented, the plane strain fracture toughness of the aluminum MMCs was in the range of 11 to 17 ksi$\sqrt{\text{in}}$ (12 to 19 MPa$\sqrt{\text{m}}$), well below the level that would be expected of Al-Si-Mg alloys; however, the very high silicon content of 361.0 may also contribute to the lower toughness.

Table 8.26 Relative ratings of resistance to general corrosion and to stress-corrosion cracking of aluminum casting alloys

		Resistance to corrosion	
Alloy	Temper	General(a)	SCC(b)
Sand castings			
208.0	F	B	B
224.0	T7	C	B
240.0	F	D	C
242.0	All	D	C
A242.0	T75	D	C
249.0	T7	C	B
295.0	All	C	C
319.0	F, T5	C	B
	T6	C	C
355.0	All	C	A
C355.0	T6	C	A
356.0	T6, T7, T71, T51	B	A
A356.0	T6	B	A
443.0	F	B	A
512.0	F	A	A
513.0	F	A	A
514.0	F	A	A
520.0	T4	A	C
535.0	F	A	A
B535.0	F	A	A
705.0	T5	B	B
707.0	T5	B	C
710.0	T5	B	B
712.0	T5	B	C
713.0	T5	B	B
771.0	T6	C	C
850.0	T5	C	B
851.0	T5	C	B
852.0	T5	C	B
Permanent mold castings			
242.0	T571, T61	D	C
308.0	F	C	B
319.0	F	C	B
	T6	C	C
332.0	T5	C	B
336.0	T551, T65	C	B
354.0	T61, T62	C	A
355.0	All	C	A
C355.0	T61	C	A
356.0	All	B	A
A356.0	T61	B	A
F356.0	All	B	A
A357.0	T61	B	A
358.0	T6	B	A
359.0	All	B	A
B443.0	F	B	A
A444.0	T4	B	A
513.0	F	A	A
705.0	T5	B	B
707.0	T5	B	C
711.0	T5	B	A
713.0	T5	B	B
850.0	T5	C	B
851.0	T5	C	B
852.0	T5	C	B
Die castings			
360.0	F	C	A
A360.0	F	C	A
364.0	F	C	A
380.0	F	E	A
A380.0	F	E	A
383.0	F	E	A
384.0	F	E	A
390.0	F	E	A
392.0	F	E	A
413.0	F	C	A
A413.0	F	C	A
C443.0	F	B	A
518.0	F	A	A
Rotor metal(c)			
100.1	. . .	A	A
150.1	. . .	A	A
170.1	. . .	A	A

(a) Relative ratings of general corrosion resistance are in decreasing order of merit, based on exposures to NaCl solution by intermittent spray or immersion. (b) Relative ratings of resistance to SCC are based on service experience and on laboratory tests of specimens exposed to alternate immersion in 3.5% NaCl solution. A, no known instance of failure in service when properly manufactured; B, failure not anticipated in service from residual stresses or from design and assembly stresses below about 45% of the minimum guaranteed yield strength given in applicable specifications; C, failures have occurred in service with either this specific alloy/temper combination or with alloy/temper combinations of this type; designers should be aware of the potential SCC problem that exists when these alloys and tempers are used under adverse conditions. (c) For electric motor rotors. Source: Ref 28

Table 8.27 Solution potentials of cast aluminum alloys

Alloy	Temper	Type of mold(a)	Potential(b), V
208.0	F	S	−0.77
238.0	F	P	−0.74
295.0	T4	S or P	−0.70
	T6	S or P	−0.71
	T62	S or P	−0.73
296.0	T4	S or P	−0.71
308.0	F	P	−0.75
319.0	F	S	−0.81
	F	P	−0.76
355.0	T4	S or P	−0.78
	T6	S or P	−0.79
356.0	T6	S or P	−0.82
443.0	F	S	−0.83
	F	P	−0.82
514.0	F	S	−0.87
520.0	T4	S or P	−0.89
710.0	F	S	−0.99

(a) S, sand; P, permanent. (b) Potential versus standard calomel electrode measured in an aqueous solution of 53 g/L NaCl plus 3 g/L H_2O_2 at 25 °C (77 °F). Source: Ref 28

Table 8.28 Typical physical properties of cast aluminum metal matrix composites (MMCs)

Metric values calculated from engineering values

Alloy	MMC designation	Temper	Density lb/in.^{3}	Density g/cm^3	Specific gravity	Average coefficient of thermal expansion 68-212 °F per °F	Average coefficient of thermal expansion 20-100 °C per °C	Approx melting range °F	Approx melting range °C	Thermal conductivity At 72 °F Eng. units	Thermal conductivity At 25 °C W/m · K	Electrical conductivity(c) At 66 °F Volumemb;0 %IACS	Electrical conductivity(c) At 66 °F Weight %IACS	Electrical conductivity(c) At 25 °C Volume MS/m	Electrical conductivity(c) At 25 °C Weight MS/m	Specific heat At 66 °Fmb;0 Btu/lb · °F	Specific heat At 20 °C J/kg · °C	Poisson's ratio
Sand and permanent mold casting																		
339.0	339.0/SiC/10p	F	0.099	2.75	2.75	11.2	20.2	...	...	...	...	...	...	...	...	...	...	...
		O	0.099	2.75	2.75	11.2	20.2	...	...	...	...	...	...	...	...	...	...	...
		T5	0.099	2.75	2.75	11.2	20.2	...	...	...	...	...	...	...	...	...	...	...
		T6	0.999	2.75	2.75	11.2	20.2	...	...	...	...	...	...	...	...	...	...	...
	339.0/SiC/20p	F	0.102	2.81	2.81	9.9	17.8	...	...	83.8	145	...	...	...	...	0.197	824	...
		O	0.102	2.81	2.81	9.9	17.8	...	...	...	...	...	...	...	...	...	...	...
		T5	0.102	2.81	2.81	9.9	17.8	...	...	...	...	...	...	...	...	...	...	...
		T6	0.102	2.81	2.81	9.9	17.8	...	...	...	...	...	...	...	...	...	...	...
359.0	359.0/SiC/10p	T6	0.098	2.71	2.71	11.5	20.7	1045-1115	565-605	...	...	...	...	...	...	0.210	879	...
	359.0/SiC/20p	O	0.100	2.77	2.77	9.7	17.5	1045-1115	565-605	...	...	...	...	...	...	0.200	837	...
		T6	0.100	2.77	2.77	9.7	17.5	1045–1115	565–605	106.9	185	...	...	...	...	0.200	837	...
		T71	0.100	2.77	2.77	9.7	17.5	1045-1115	565-605	116.1	201	...	...	...	...	0.200	837	...
Sand casting																		
361.0(a)	361.0/SiC/30p	T6	0.100	2.78	2.78	8.0	14.5	...	...	92.5	160	...	...	...	...	0.190	820	
Investment casting																		
361.0(a)	361.0/SiC/30p	T6P	0.101	2.80	2.80	7.8	14.1	...	...	92.5	160	...	...	...	...	0.190	820	0.29
	361.0/SiC/40p	F	0.104	2.87	2.87	6.6	11.9	...	...	106.4	183	...	...	...	...	0.170	763	...
		T6	0.104	2.87	2.87	6.6	11.9	...	...	106.4	183	...	...	...	...	0.170	763	0.28
Die casting																		
301.0(b)	301.0/SiC/10p	F	0.100	2.76	2.76	10.7	19.3	1000-1100	540-595	71.6	124	22.0	71	13	41	0.201	842	0.3
		O	0.100	2.76	2.76	10.7	19.3	1000-1100	540–595	...	...							
		T5	0.100	2.76	2.76	10.7	19.3	1000–1100	540–595	...	...							
301.0(b)	301.0/SiC/20p	F	0.102	2.82	2.82	9.4	16.9	1000-1100	540-595	83.2	144	20.5	78	12	45	0.198	829	0.29
		O	0.102	2.82	2.82	9.4	16.9	1000-1100	540-595	...	...							
		T5	0.102	2.82	2.82	9.4	16.9	1000–1100	540–595	...	...							
303.0(b)	303.0/SiC/10p	F	0.097	2.65	2.65	...	...			...	161	32.7	125	19	72	0.208	871	...
		O	0.097	2.65	2.65													
		T5	0.097	2.65	2.65													
303.0(b)	303.0/SiC/20p	F	0.098	2.71	2.71					...	168	24.7	94	14	55	0.193	808	0.29
		O	0.098	2.71	2.71													
		T5	0.098	2.71	2.71													
361.0(a)	361.0/SiC/18p	F	0.100	2.77	2.77	9.0	16.2	...	...	76.3	132	...	...	...	...	0.180	802	0.31
	361.0/SiC/30p	F	0.101	2.80	2.80	7.8	14.1	...	...	92.3	158	...	...	...	...	...	...	0.29
		T5P	0.101	2.80	2.80	7.8	14.1	...	...	92.3	158	...	...	...	...	...	...	0.29

(a) In referenced publications, aluminum casting alloy 361.0 is referred to as Al-10Si-1Mg or Al-10Si-1Mg-1Fe. (b) In referenced NADCA specifications, aluminum casting alloys 301.0 and 303.0 are referred to as 360 and 380, respectively. Source: Ref 7, 29, 30

Table 8.29 Typical mechanical properties of cast aluminum metal matrix composites (MMCs) at room temperature

Metric values calculated from engineering values. Values are representative of separately cast test bars, not of specimens taken from commercial castings.

			Tension											
			Ultimate strength		Yield strength(a)		Elongation in 2 in. or 4D,		Fatigue endurance limit(b)		Fracture toughness (K_{Ic})		Modulus of elasticity(c)	
Matrix alloy	MMC designation	Temper	ksi	MPa	ksi	MPa	%	Hardness HRB	ksi	MPa	ksi · in.$^{1/2}$	MPa · m$^{1/2}$	10^6 psi	GPa
Sand and permanent mold casting														
339.0	339.0/SiC/10p	F	37	255	26	179	0.7	57	...	...	...	...	12.8	88
		O	33	228	20	138	1.0	43	...	...	...	...	12.8	88
		T5	39	269	36	248	0.3	63	...	...	...	...	12.8	88
		T6	54	372	52	359	0.3	79	...	...	...	...	12.8	88
	339.0/SiC/20p	F	38	262	31	214	0.4	70	...	...	...	...	14.6	101
		O	33	228	27	186	0.4	53	...	...	...	...	14.6	101
		T5	41	283	39	269	0.2	75	...	...	...	...	14.6	101
		T6	54	372	...	...	...	86	...	...	...	...	14.6	101
359.0	359.0/SiC/10p	T6	49	338	44	303	1.2	55	...	...	15.8	17.4	12.5	86
	359.0/SiC/20p	O	32	221	24	165	2.8	73	...	...	...	...	14.4	99
		T6	52	359	49	338	0.4	77	7	50	14.4	15.9	14.4	99
		T71	38	262	31	214	1.9	...	...	...	...	...	14.4	99
Sand casting														
361.0(e)	361.0/SiC/30p	T6	54	371	...	...	0.4	...	19	132	13.4	14.7	18.1	125
Investment casting														
361.0(e)	361.0/SiC/30p	T6	51	350	38	260	0.5	...	...	...			18.1	125
	361.0/SiC/40p	F	33	226	29	199	0.5	...	17	115	11.0	12.1	21.9	151
		T6	54	370	39	270	0.4	...	22	150	...	...	21.3	147
Die casting														
301(d)	301.0/SiC/10p	F	50	345	35	241	1.2	77	...	...	...	...	13.6	94
		O	40	276	22	152	1.7	55	...	...	...	...	13.6	94
		T5	54	372	48	331	0.7	84	...	...	...	...	13.6	94
	301.0/SiC/20p	F	51	352	44	303	0.4	82	22	130	...	...	16.5	114
		O	44	303	27	186	0.8	62	...	...	...	...	16.5	114
		T5	58	400	...	...	...	87	...	...	...	...	16.5	114
303(d)	303.0/SiC/10p	F	45	310	32	221	0.9	...	...	...	...	...	13.2	91
		O	36	248	21	145	2.0	...	...	...	...	...	13.2	91
		T5	51	352	46	317	0.5	...	...	...	...	...	13.2	91
	303.0/SiC/20p	F	44	303	36	248	0.5	...	...	...	...	...	15.7	108
		O	38	262	23	159	1.5	...	...	...	...	...	15.7	108
		T5	53	365	49	338	0.3	...	...	...	...	...	15.7	108
361.0(e)	361.0/SiC/18p	F	43	295	32	220	1.0	...	...	...	11.7	12.8	15.4	106
	361.0/SiC/30p	F	45	309	22	155	0.4	...	...	...	...	...	18.1	125
		T5P	44	307	34	235	0.3	...	...	...	...	...	18.1	125

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 10,000,000 cycles of axial stress stress (R = 0.1) fatigue loading (Source: Duralcan, USA). (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. (d) In referenced publications, aluminum casting alloys 301.0 and 303.0 are referred to as 380 and 360, respectively, obsolete designations. (e) In referenced publications, aluminum casting alloy 361.0 is referred to as Al-10Si-1Mg or Al-10Si-1Mg-1Fe. Source: Ref 7, 29, 30

Table 8.30 Relative casting and finishing characteristics of die cast aluminum metal matrix composites (MMCs)

Ratings are from 1 (most desirable) to 5 (least desirable). In referenced NADCA specifications, aluminum casting alloys are referred to as 360 and 380, respectively.

		Casting characteristics				Finishing characteristics					Performance characteristics		
									Anodizing				
Alloy	MMC designation	Resistance to hot cracking	Fluidity/ die filling capacity	Pressure tightness	Anti-soldering to die	Machin-ability	Polish-ability	Electro-platibility	Appearance	Protection	Corrosion resistance	Elevated temperature strength	Resistance to wear
301.0	301.0/SiC/10P	1	1	2	3	4	5	2	4	5	5	1	1
	301.0/SiC/20P	1	1	2	3	4	5	2	4	5	5	1	1
303.0	303.0/SiC/10P	1	1	2	2	4	5	2	4	4	3	1	1
	303.0/SiC/20P	1	1	2	2	4	5	2	4	4	3	1	1

Source: Ref 7; Duralcan cited as original reference

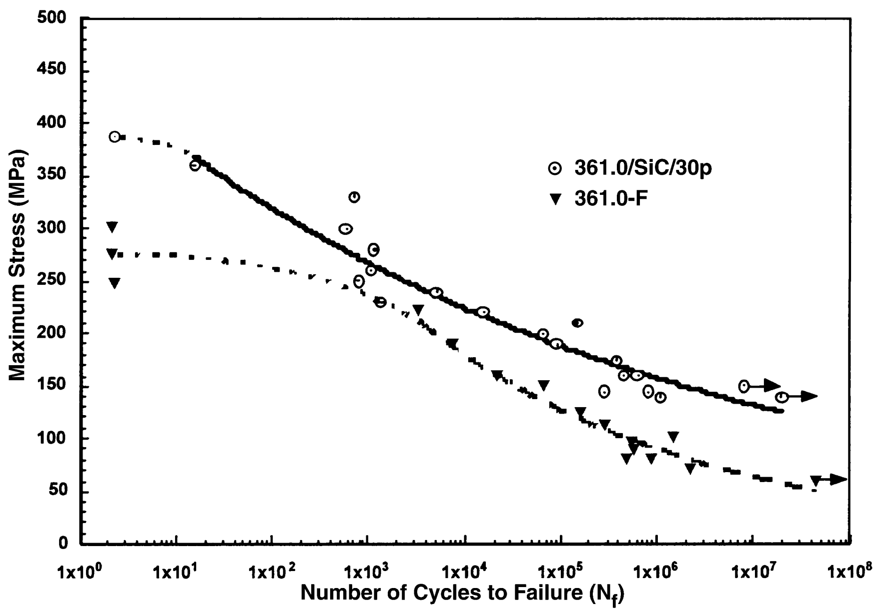

Fig. 8.30 Fatigue curves ($R = -1.0$) for cast reinforced and unreinforced alloy 361.0 at room temperature. The reinforced composite is 361.0/SiC/30p. Source: Ref 30

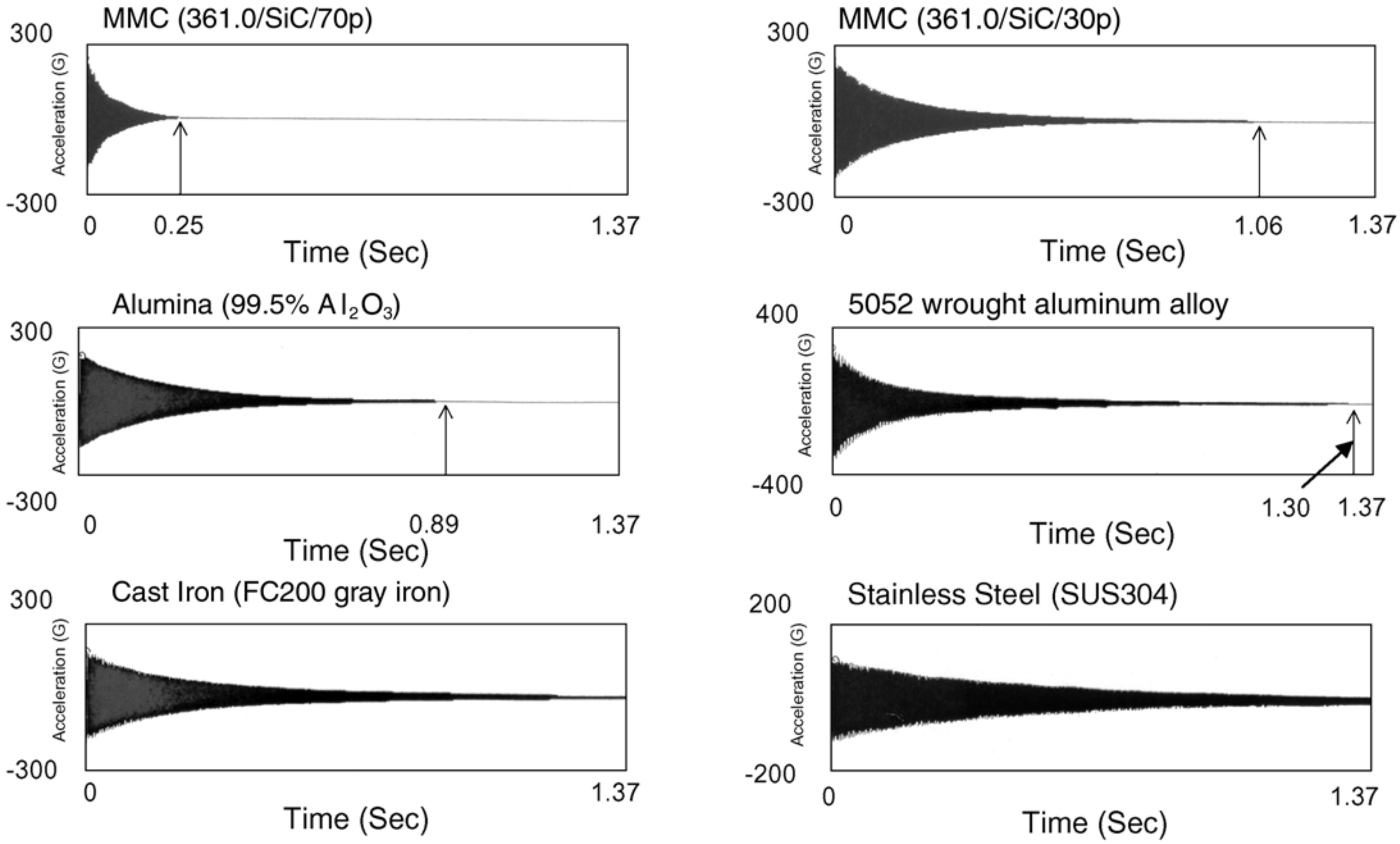

Fig. 8.31 Comparison of vibration damping performance for selected aluminum MMCs and other structural alloys. Frequency range, 0.01 Hz to 5 kHz; impacting force, approximately 49 lbf (220 N); specimen size, 9.4 × 1.2 × 0.4 in. (240 × 30 × 10 mm). The specimen is suspended in air and impacted in the center, then the acceleration at an edge is measured. Source: Ref 30

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Aluminum Alloy Castings: Properties, Processes, and Applications
J.G. Kaufman, E.L. Rooy, p 133-173
DOI:10.1361/aacp2004p133

DATA SET 1

Aging Response Curves

This data set contains aging response curves for a wide range of aluminum casting alloys. Included where available are both:

- *Room-temperature, or "natural," aging response curves* (Fig. D1.1 to D1.49). Properties were measured after holding specimens at room temperature for various times after casting (F temper) or after solution heat treatment (T4 temper).
- *Artificial or "high-temperature" aging response curves* (Fig. D1.50 to D1.111). Properties were measured after holding specimens at various elevated temperatures for various times from the as-cast condition or after solution heat treatment. These are captioned "high temperature," but the implication is that any artificial aging above room temperature is included.

The curves in each group are presented in the numeric sequence of the casting alloy designation.

The intent in making such measurements is to determine the extent of the effects of time and temperature on precipitation hardening or softening. All of the aging response curves presented were developed at the Alcoa Laboratories Cleveland Casting Research Division. The curves are printed with customary static mechanical property units obtained through uniaxial tensile testing. To convert strengths in ksi to SI units (MPa) multiply by 6.895.

The tensile tests were conducted in accordance with the iteration of ASTM E 8, "Standard Test Methods for Tension Testing of Metallic Materials," that was current at the time of the testing.

The aging response curves included herein are the results of measurements on individual lots considered representative of the respective alloys and tempers. They have not been normalized to any typical or average properties for the individual alloys and tempers. The testing may have predated the registry of the current alloy designation, but the composition of the tested material is within the limits of the designation. In a number of cases, the results of measurements made on several lots of the same alloy and temper are included.

The properties considered are as follows:

- *Yield strength* is determined by the 0.2% offset method.
- *Ultimate strength (tensile strength)* is the load at fracture divided by the original cross section of the specimen.
- *Elongation* is determined from a 2 in. (50 mm) gage length specimen.
- *Brinell hardness (HB)* testing employed a 4.9 kN (500 kgf) load with a 10 mm ball, in accordance with ASTM E 10.

Test specimens were separately cast, in conformance with Appendix 3, Fig. A3.1. The casting method is given in the caption if it was given in the original test document. If the process is not stated, it was not stipulated in the original record.

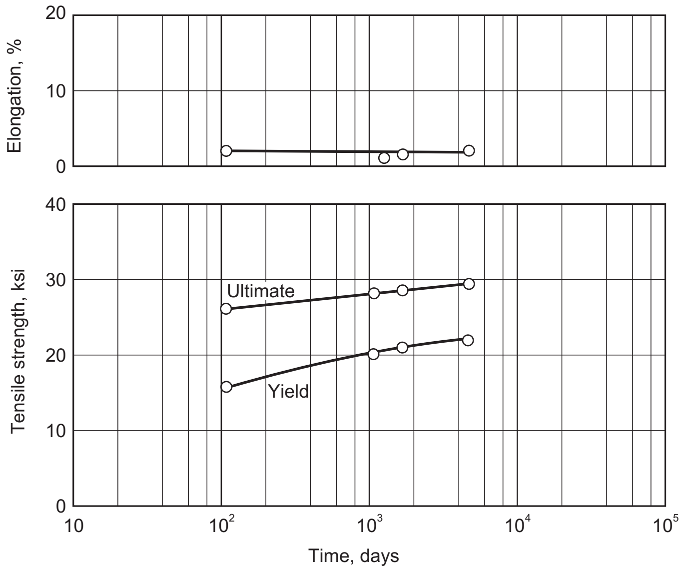

Fig. D1.1 Room-temperature aging characteristics for aluminum alloy 208.0-F, sand cast

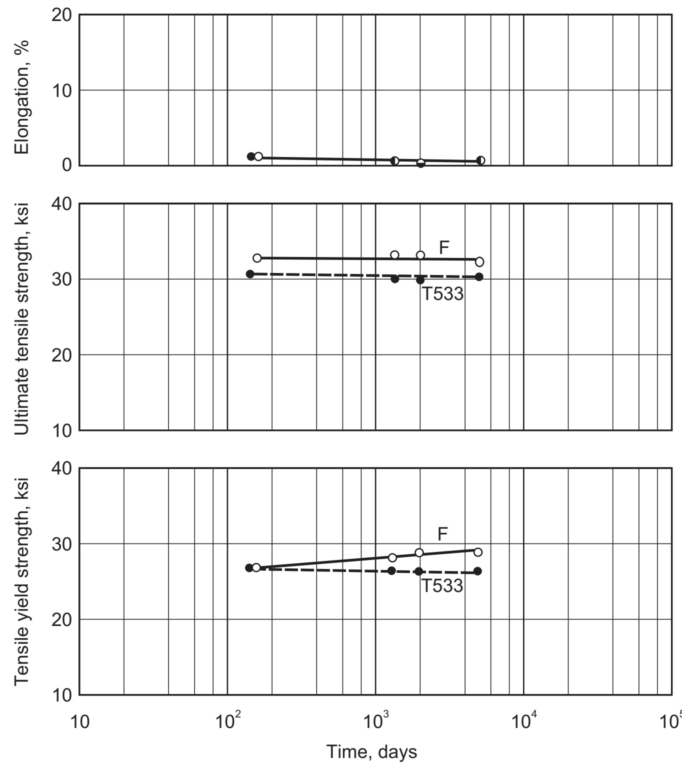

Fig. D1.2 Room-temperature aging characteristics for aluminum alloy 213.0-F and -T533, permanent mold

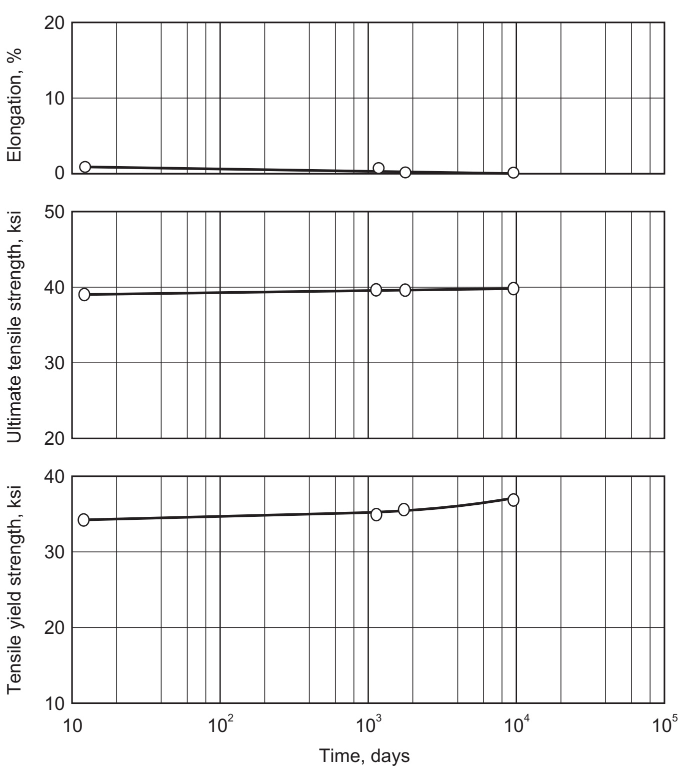

Fig. D1.3 Room-temperature aging characteristics for aluminum alloy 242.0-T571, permanent mold

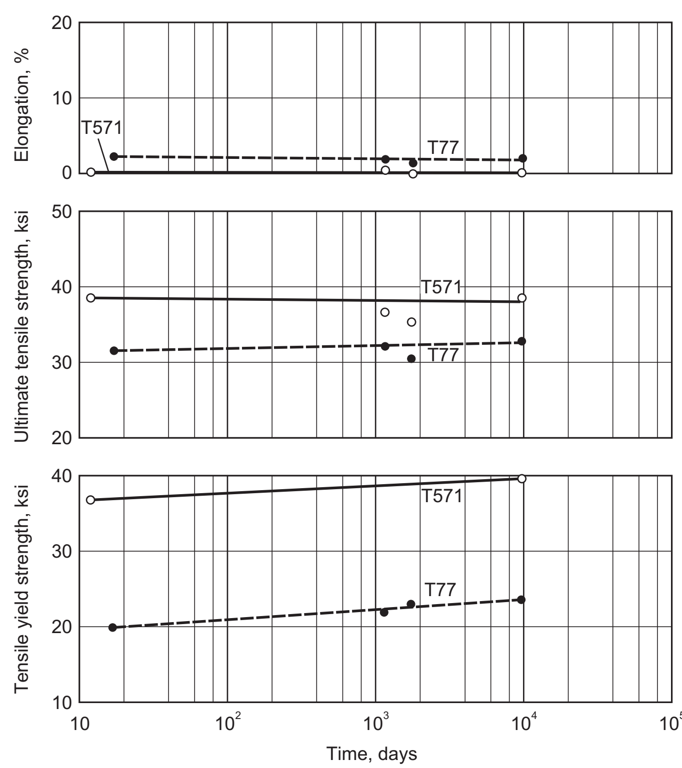

Fig. D1.4 Room-temperature aging characteristics for aluminum alloy 242.0-T571 and -T77, sand cast

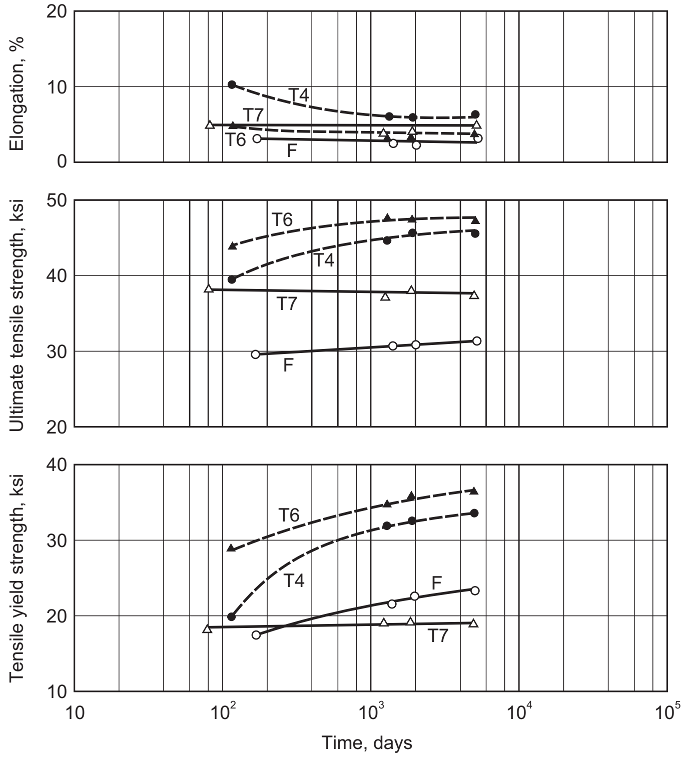

Fig. D1.5 Room-temperature aging characteristics for aluminum alloy 295.0-F, -T4, -T6, and -T7, sand cast

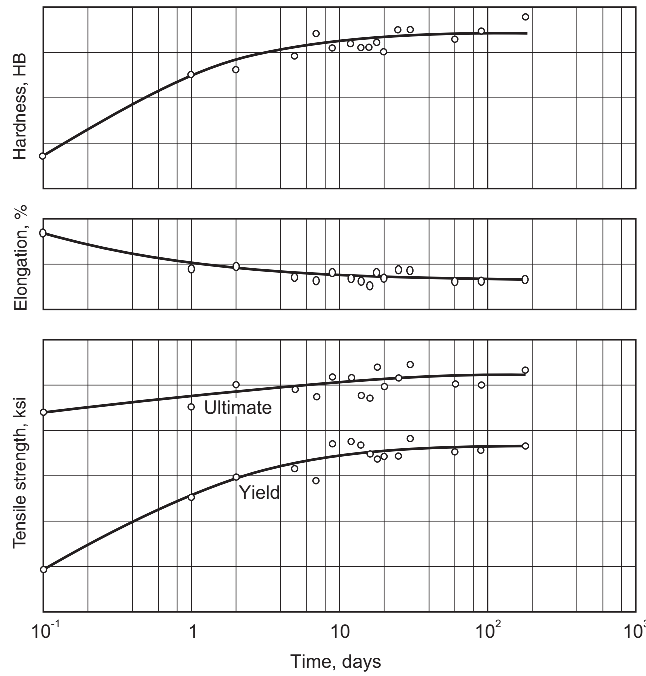

Fig. D1.6 Room-temperature aging characteristics for aluminum alloy 295.0-T4, permanent mold

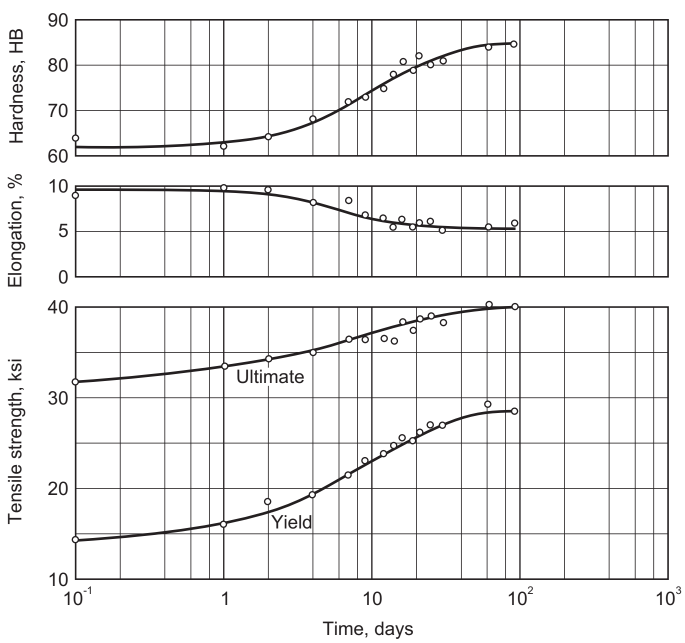

Fig. D1.7 Room-temperature aging characteristics for aluminum alloy 295.0-T4, sand cast

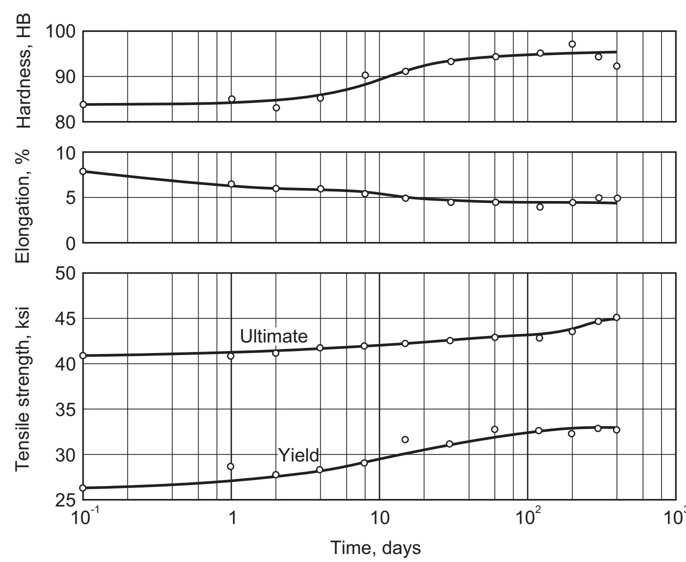

Fig. D1.8 Room-temperature aging characteristics for aluminum alloy 295.0-T6, permanent mold

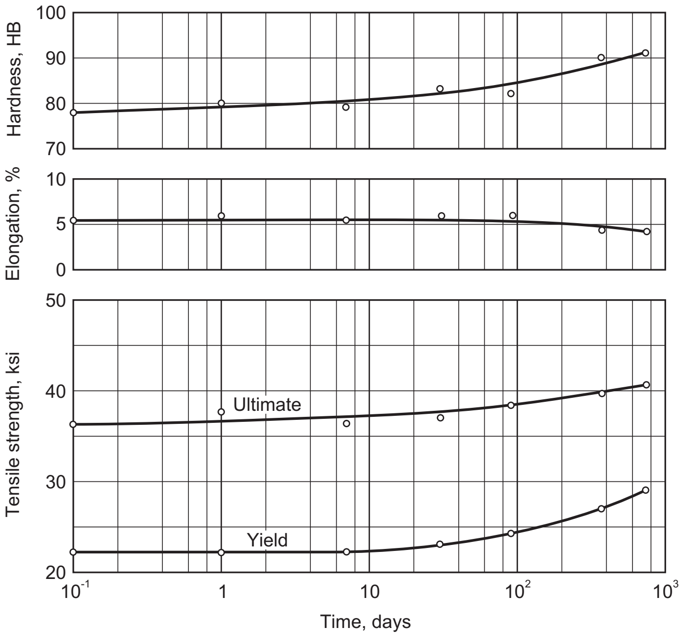

Fig. D1.9 Room-temperature aging characteristics for aluminum alloy 295.0-T6, sand cast

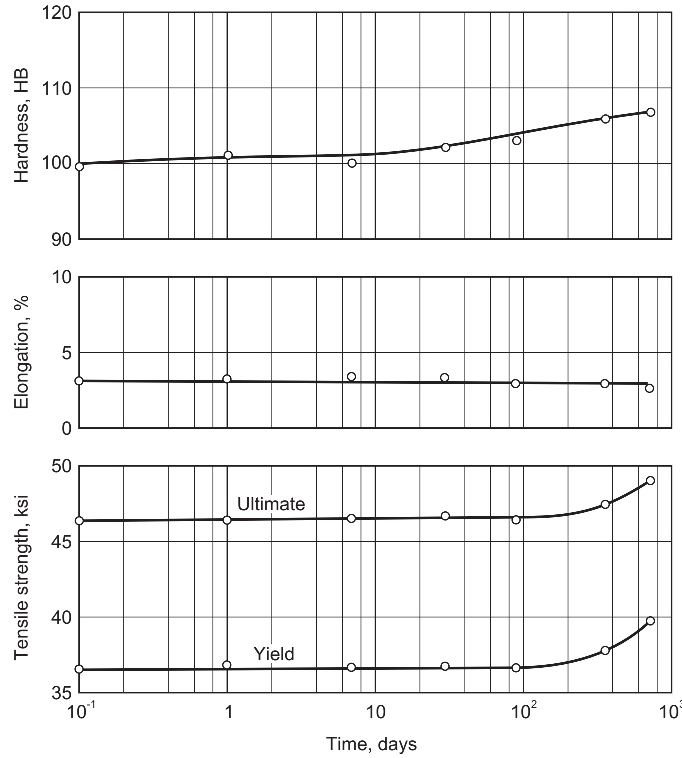

Fig. D1.10 Room-temperature aging characteristics for aluminum alloy 295.0-T62, permanent mold

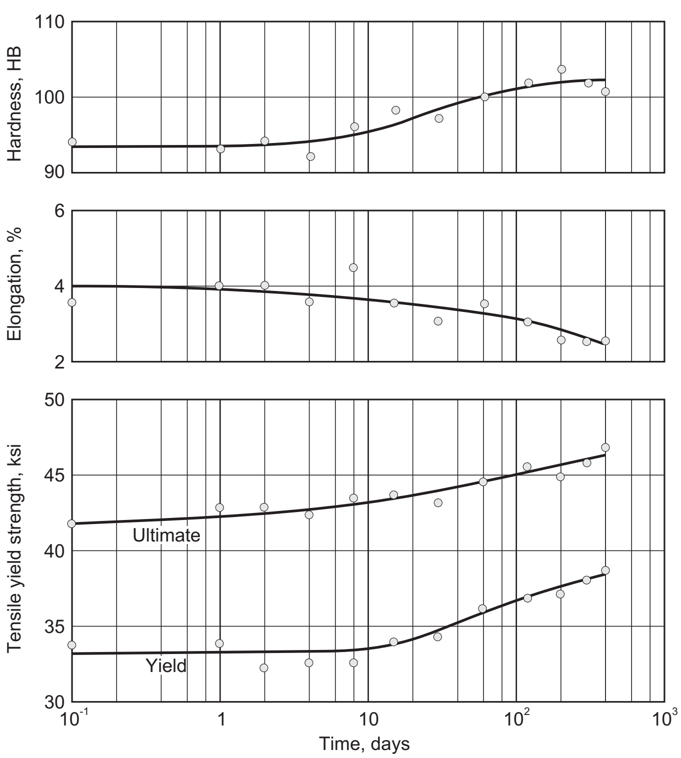

Fig. D1.11 Room-temperature aging characteristics for aluminum alloy 295.0-T62, sand cast

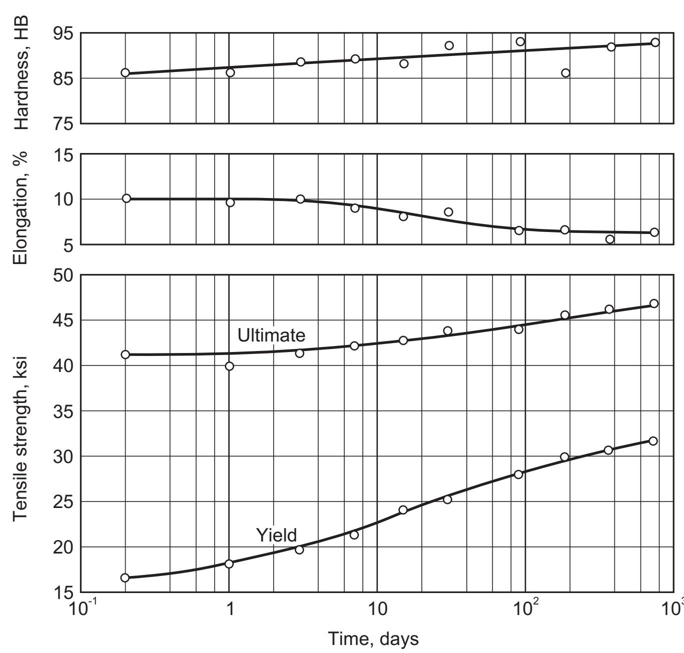

Fig. D1.12 Room-temperature aging characteristics for aluminum alloy 296.0-T4, permanent mold

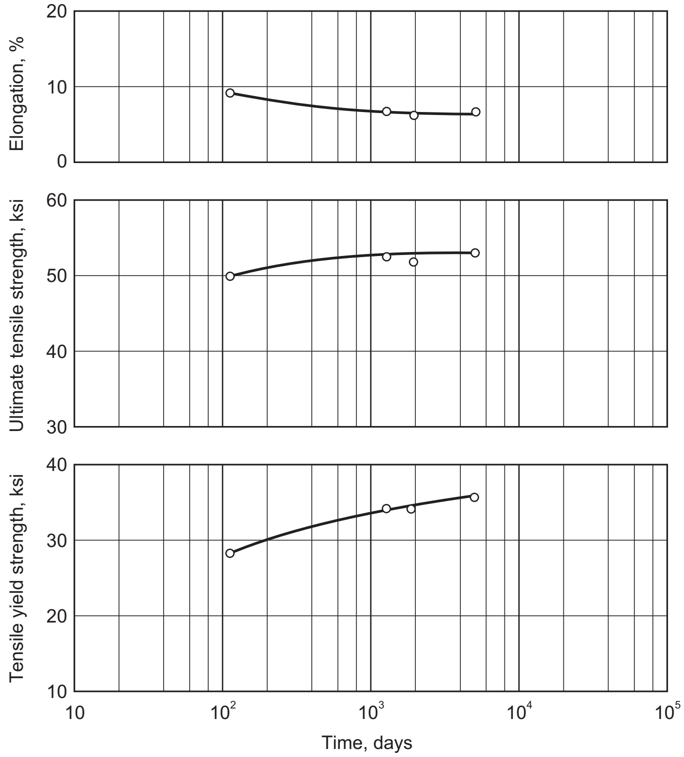

Fig. D1.13 Room-temperature aging characteristics for aluminum alloy 296.0-T6, permanent mold

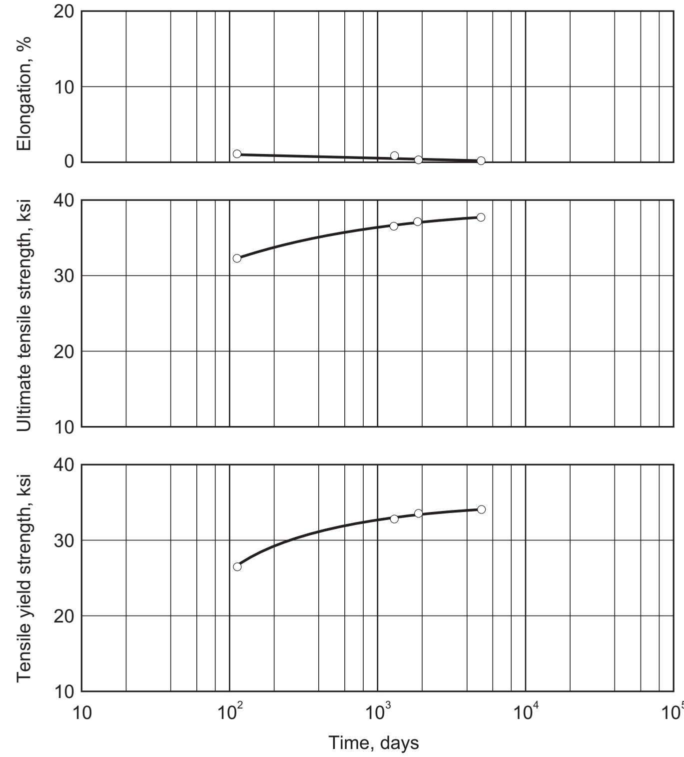

Fig. D1.14 Room-temperature aging characteristics for aluminum alloy 296.0-T6, sand cast

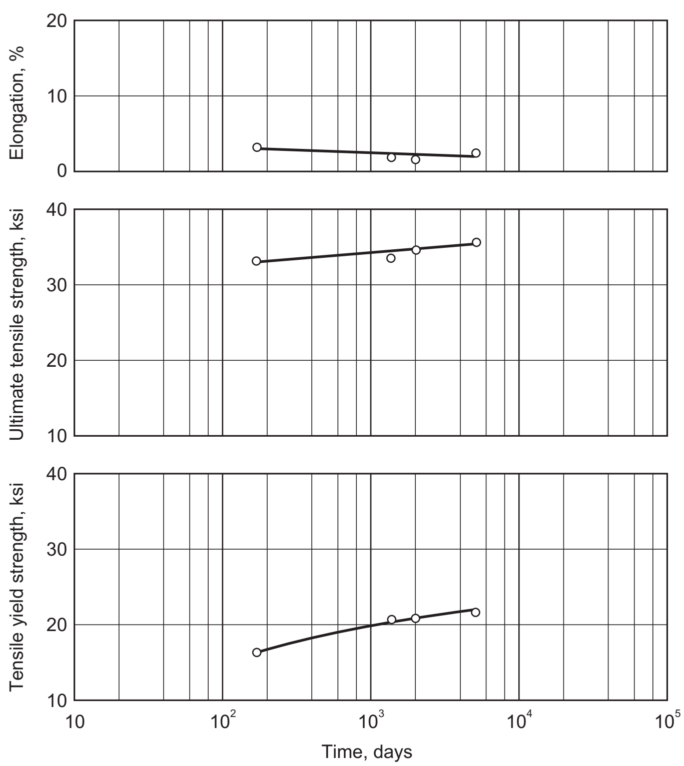

Fig. D1.15 Room-temperature aging characteristics for aluminum alloy 308.0-F, permanent mold

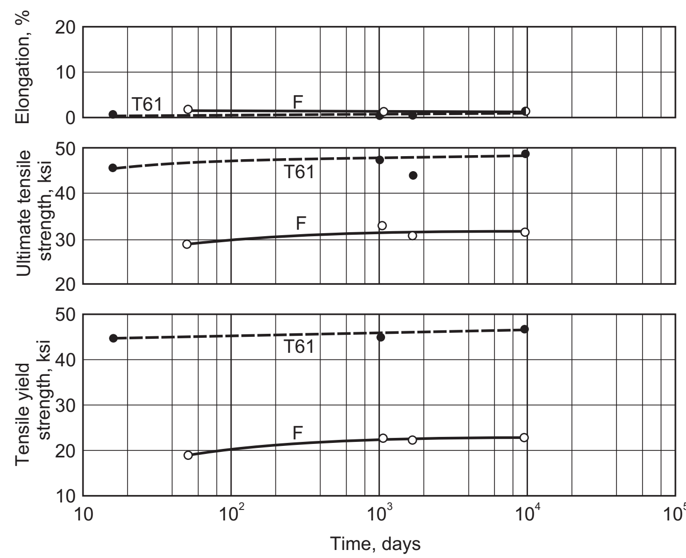

Fig. D1.16 Room-temperature aging characteristics for aluminum alloy 319.0-F and -T61, permanent mold

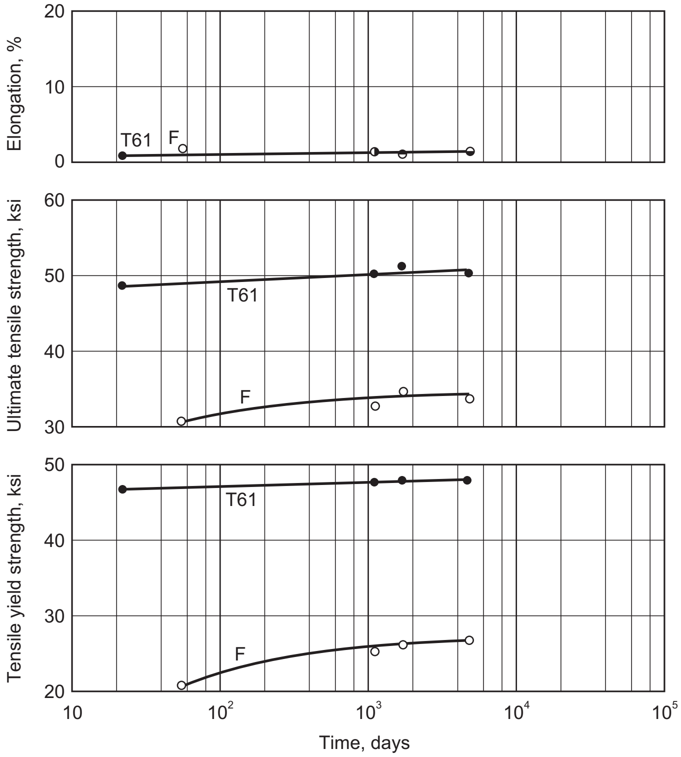

Fig. D1.17 Room-temperature aging characteristics for aluminum alloy 319.0-F, and -T61, sand cast

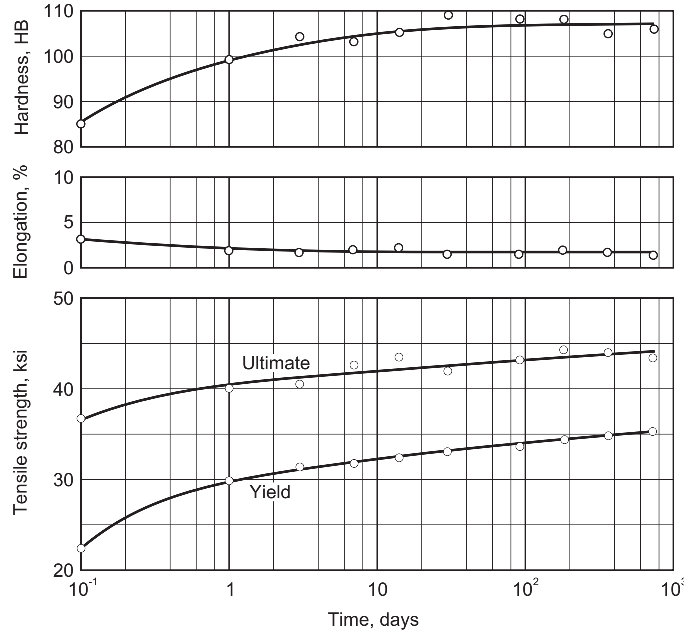

Fig. D1.18 Room-temperature aging characteristics for aluminum alloy 319.0-T4

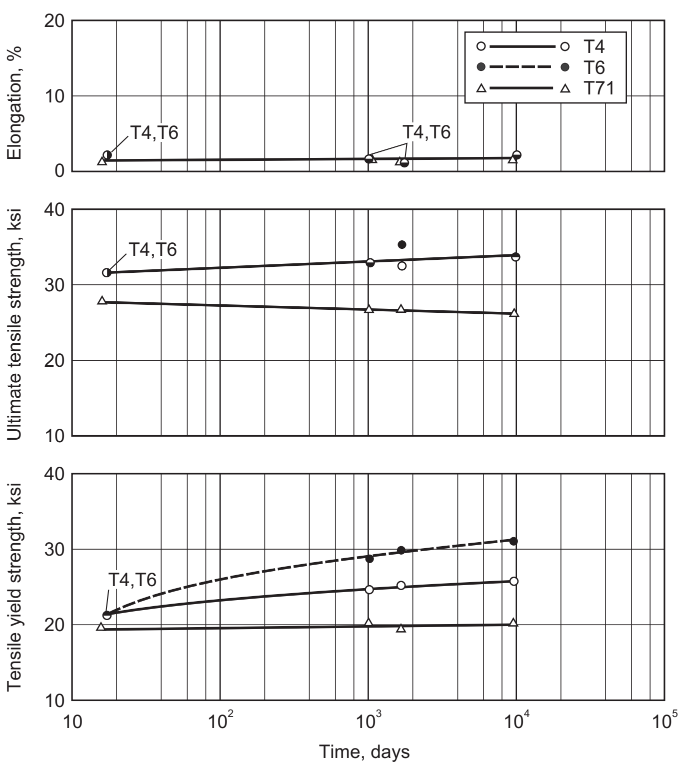

Fig. D1.19 Room-temperature aging characteristics for aluminum alloy 319.0-T4, -T6, and -T71, permanent mold

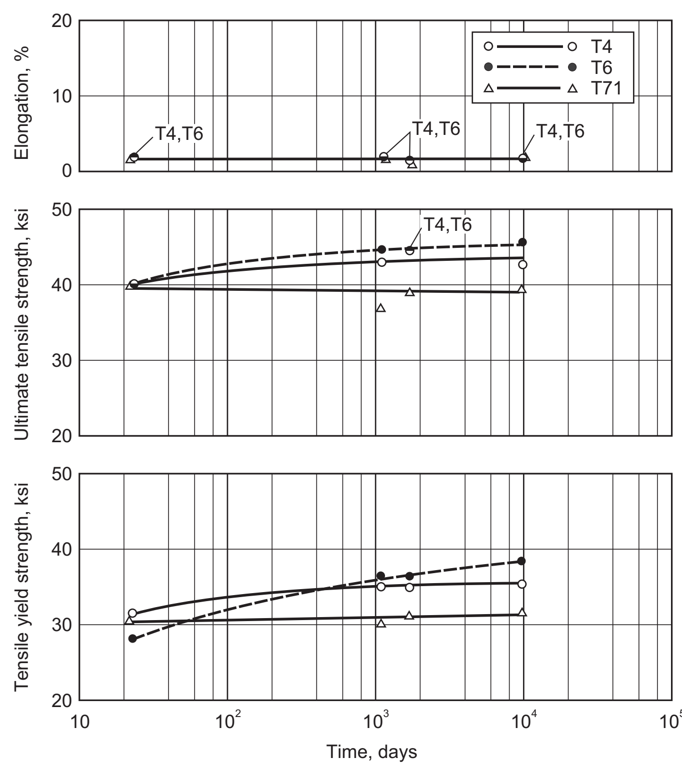

Fig. D1.20 Room-temperature aging characteristics for aluminum alloy 319.0-T4, -T6, and -T71, sand cast

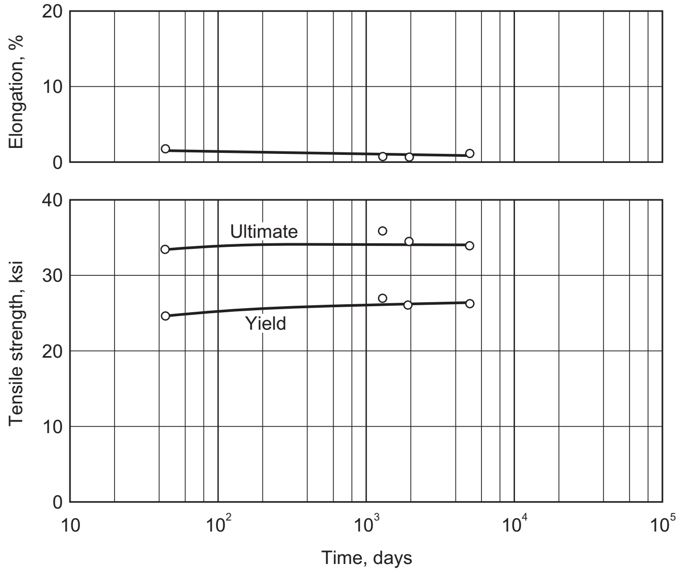

Fig. D1.21 Room-temperature aging characteristics for aluminum alloy 333.0-T5, permanent mold

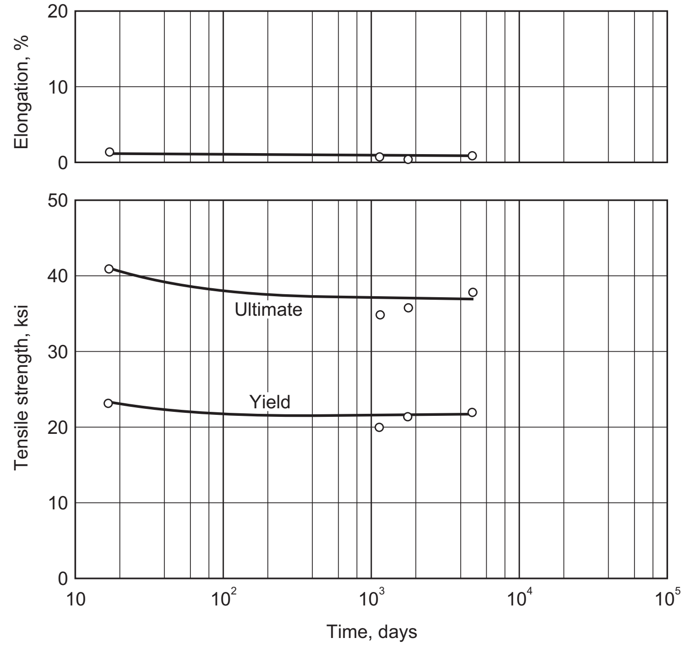

Fig. D1.22 Room-temperature aging characteristics for aluminum alloy 336.0-T551, permanent mold

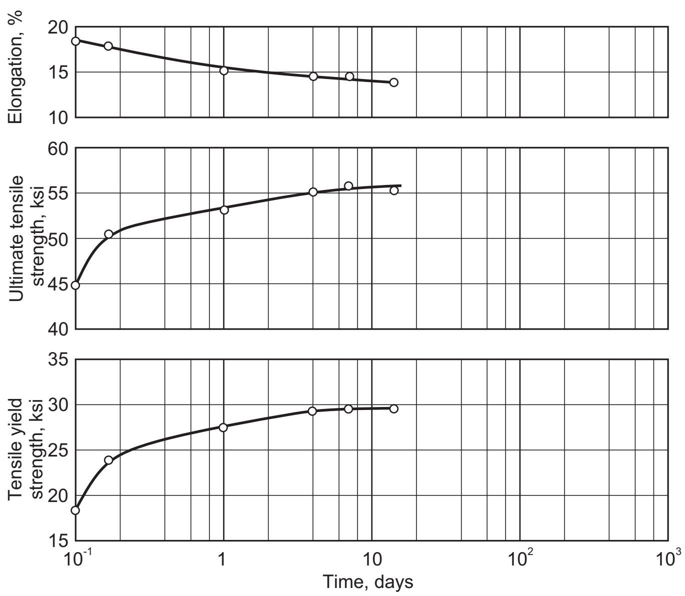

Fig. D1.23 Room-temperature aging characteristics for aluminum alloy 354.0-T4, permanent mold

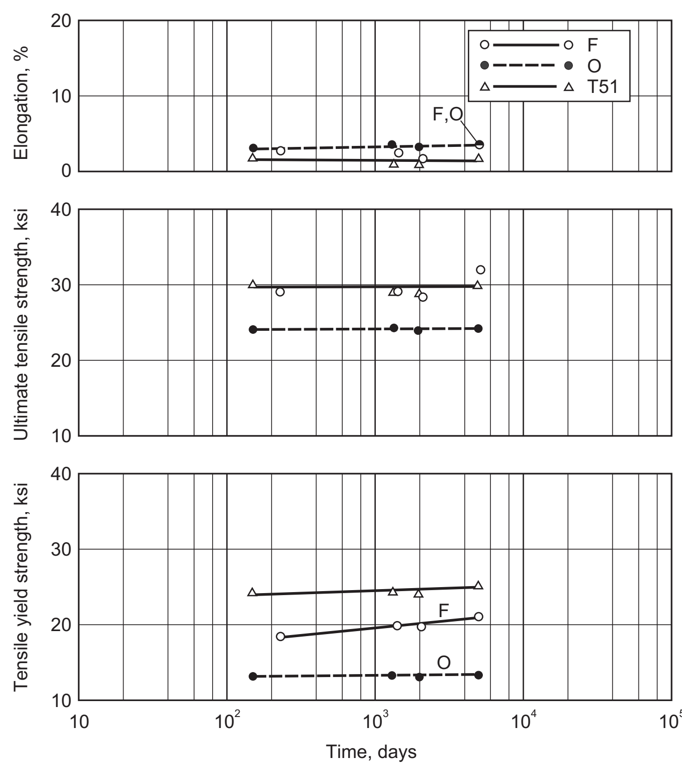

Fig. D1.24 Room-temperature aging characteristics for aluminum alloy 355.0-F, -O, and -T51, permanent mold

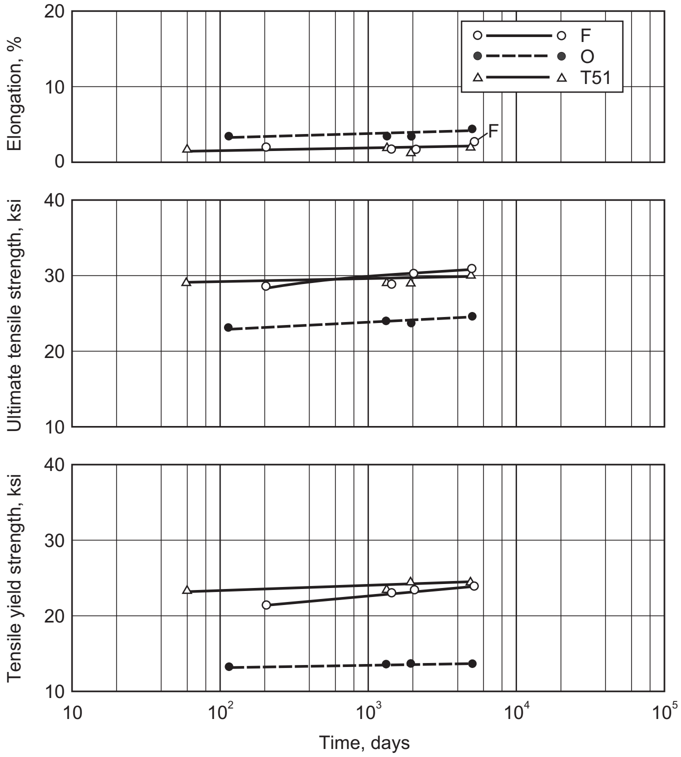

Fig. D1.25 Room-temperature aging characteristics for aluminum alloy 355.0-F, -O, and -T51, sand cast

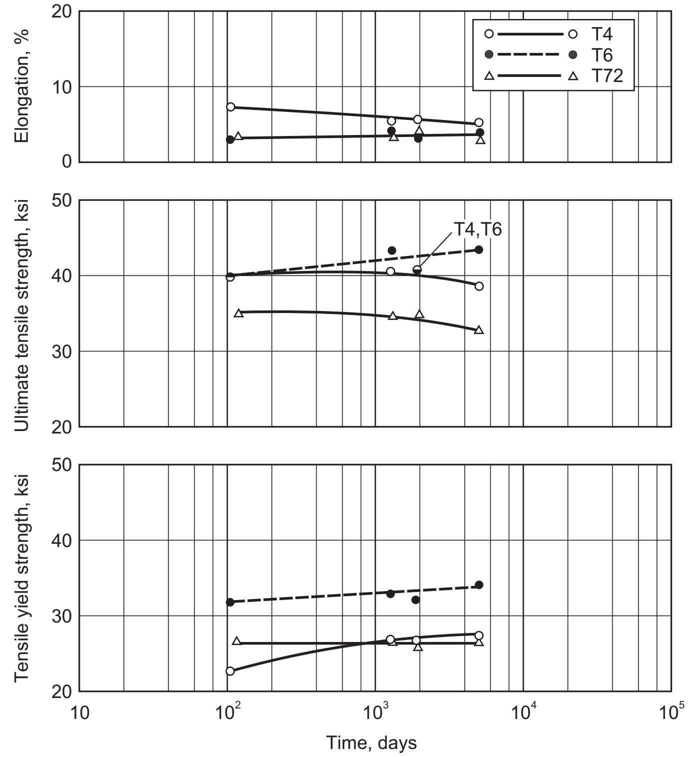

Fig. D1.26 Room-temperature aging characteristics for aluminum alloy 355.0-T4, -T6, and -T72, permanent mold

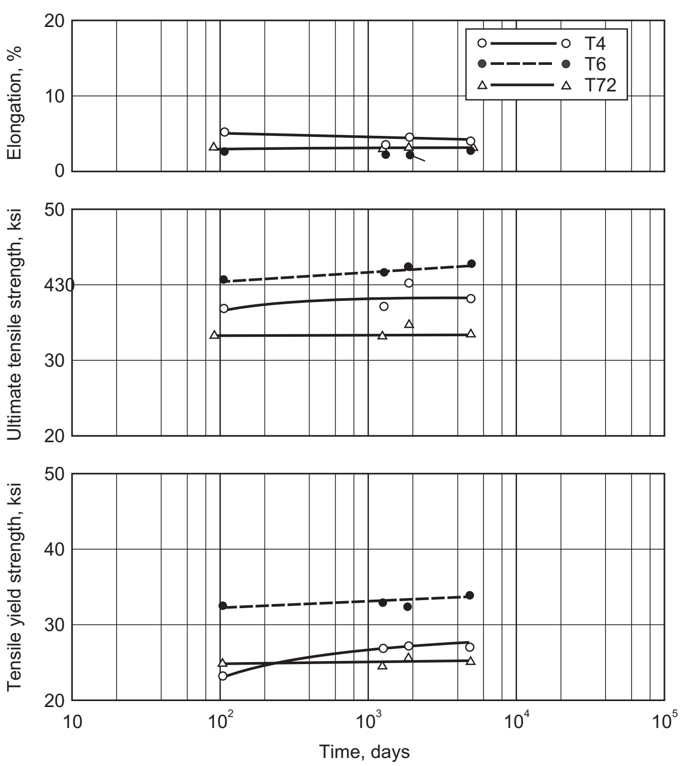

Fig. D1.27 Room-temperature aging characteristics for aluminum alloy 355.0-T4, -T6, and -T72, sand cast.

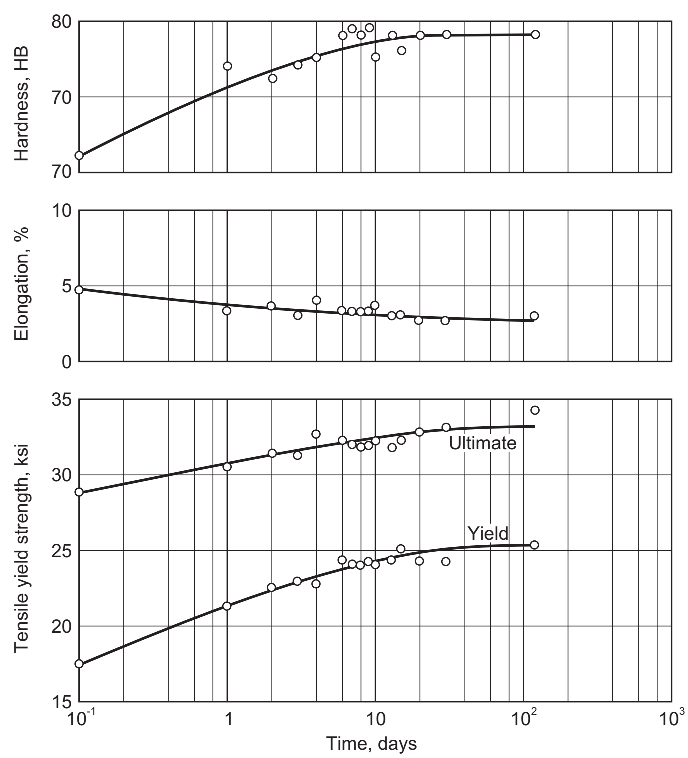

Fig. D1.28 Room-temperature aging characteristics for aluminum alloy 355.0-T4, aging time 120 days and less

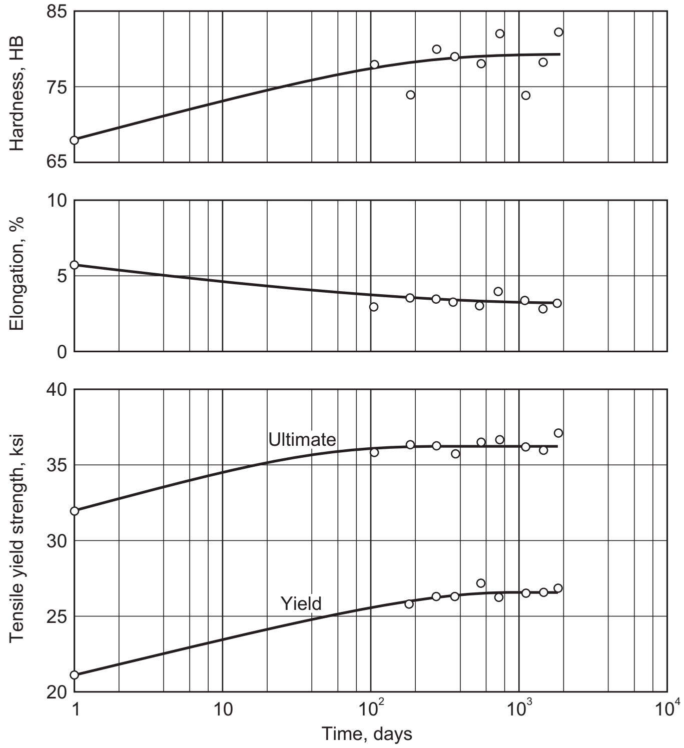

Fig. D1.29 Room-temperature aging characteristics for aluminum alloy 355.0-T4, longer-term data approaching 2000 days

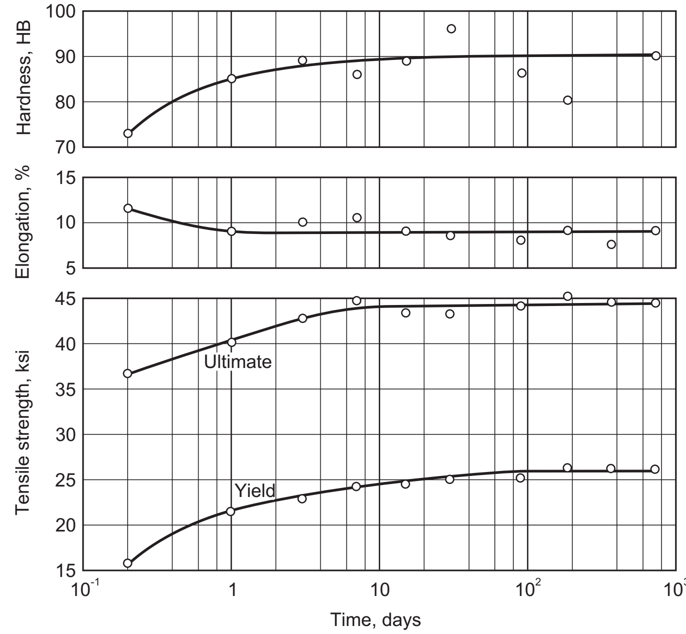

Fig. D1.30 Room-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

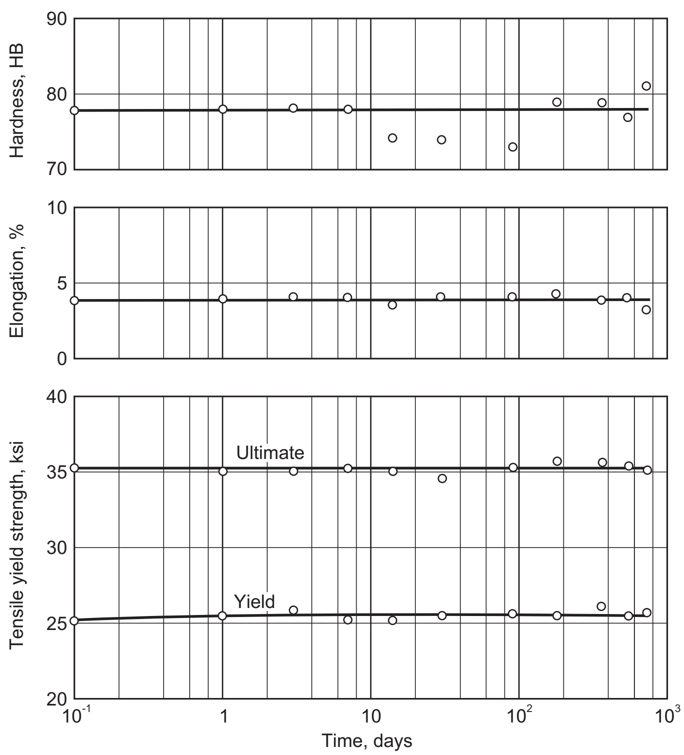

Fig. D1.31 Room-temperature aging characteristics for aluminum alloy 355.0-T6

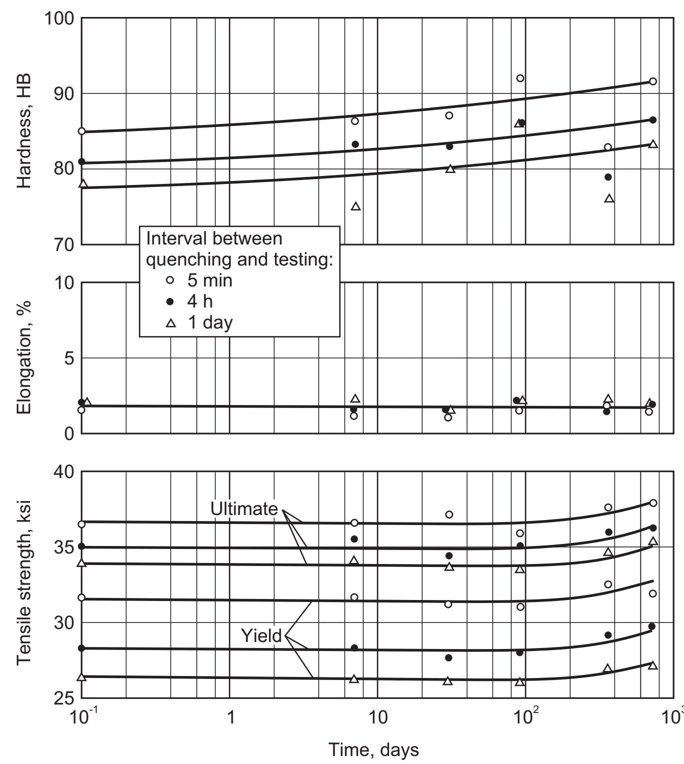

Fig. D1.32 Room-temperature aging characteristics for aluminum alloy 355.0-T6. Effect of time interval between quenching and aging on properties

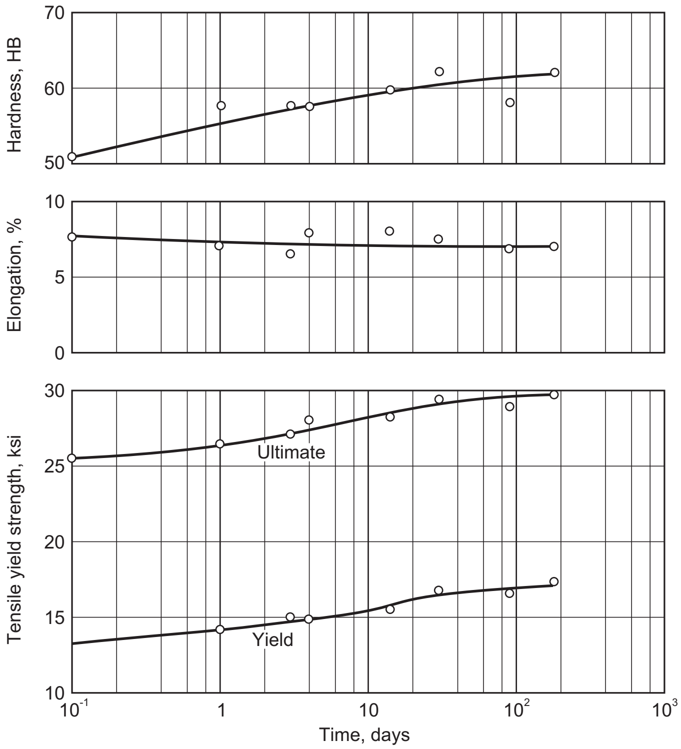

Fig. D1.33 Room-temperature aging characteristics for aluminum alloy 356.0-T4. Shorter-term data, less than 200 days

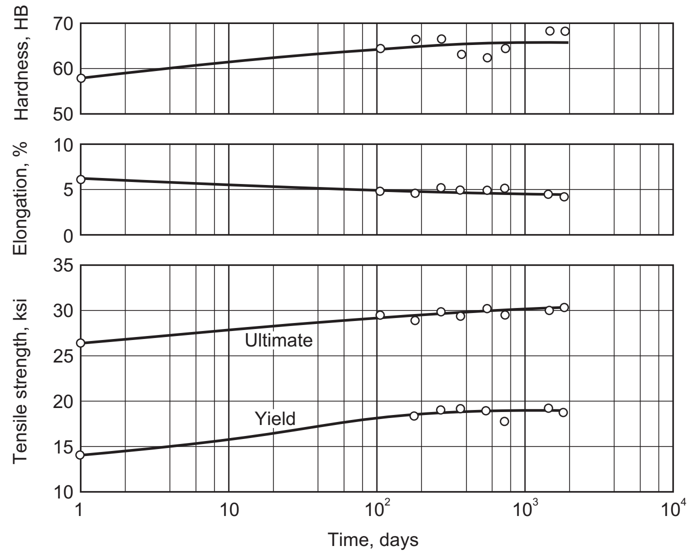

Fig. D1.34 Room-temperature aging characteristics for aluminum alloy 356.0-T4. Longer-term data, approaching 2000 days

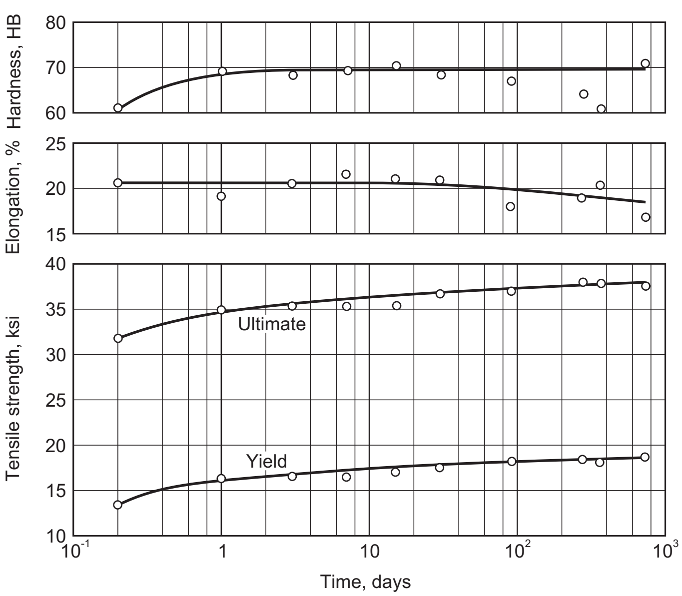

Fig. D1.35 Room-temperature aging characteristics for aluminum alloy 356.0-T4

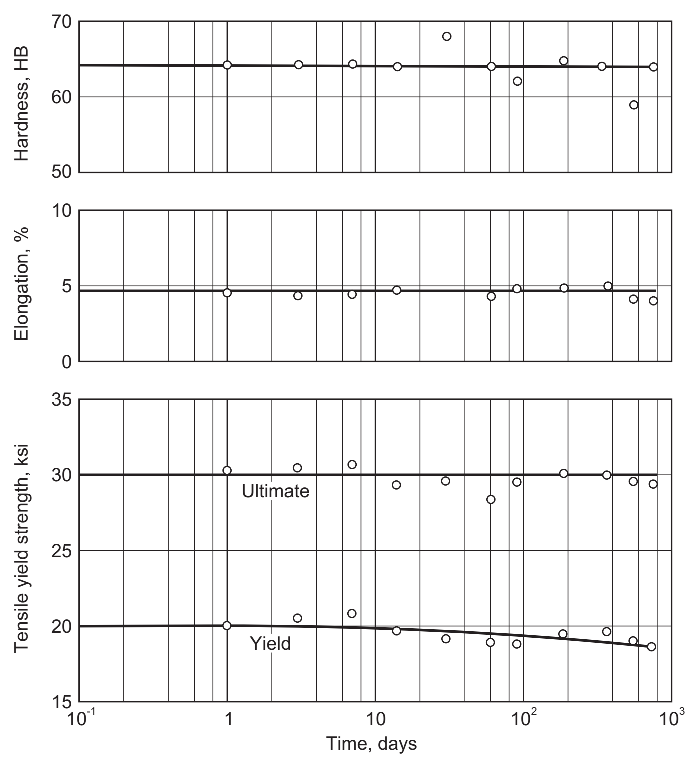

Fig. D1.36 Room-temperature aging characteristics for aluminum alloy 356.0-T6

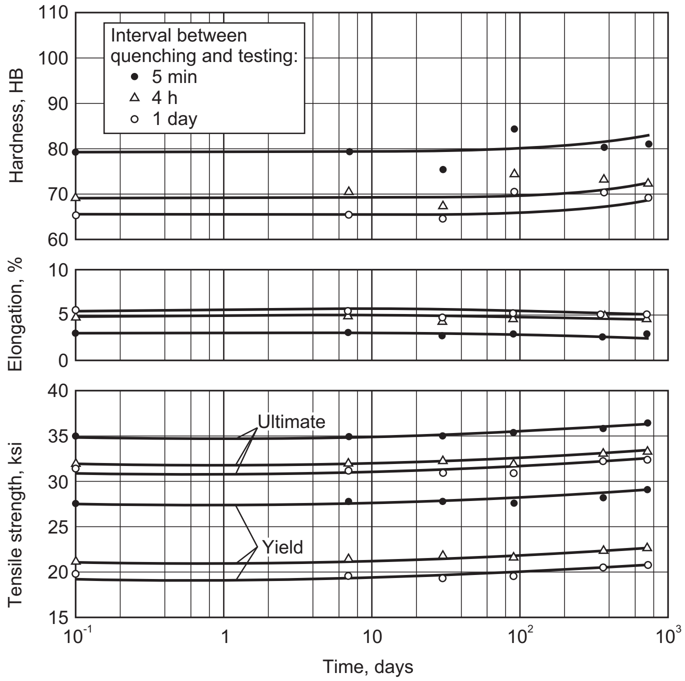

Fig. D1.37 Room-temperature aging characteristics for aluminum alloy 356.0-T6. Effect of time interval between quenching and aging

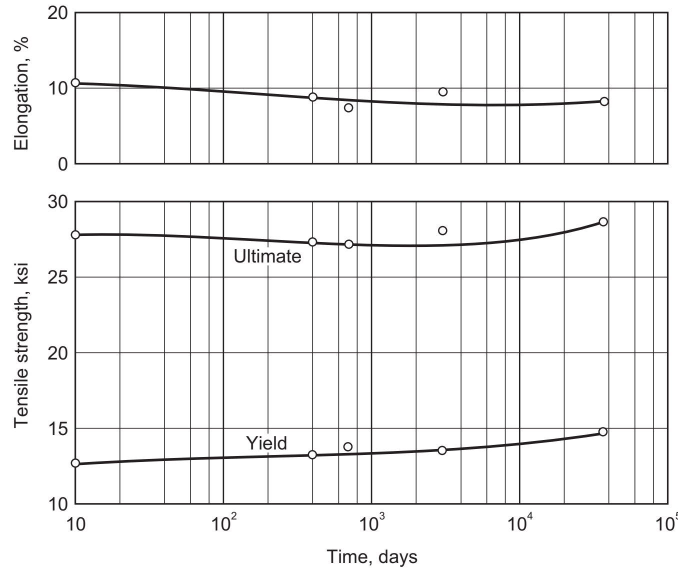

Fig. D1.38 Room-temperature aging characteristics for aluminum alloy 364.0-T4, die cast

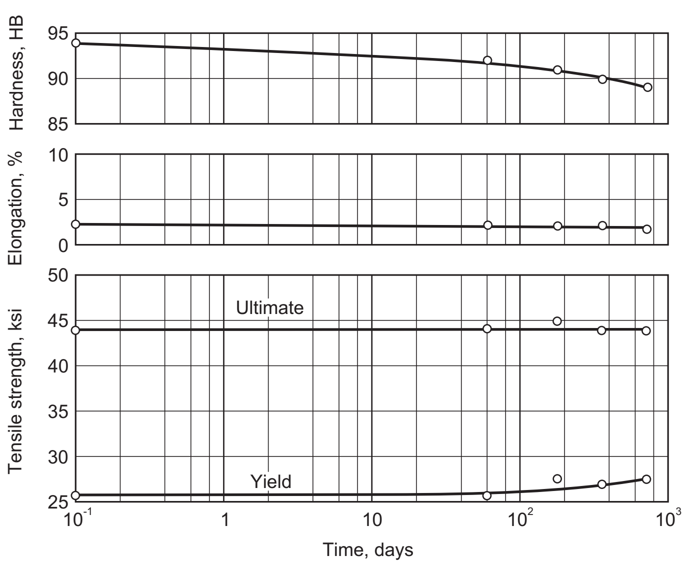

Fig. D1.39 Room-temperature aging characteristics for aluminum alloy 380.0-T5, die cast

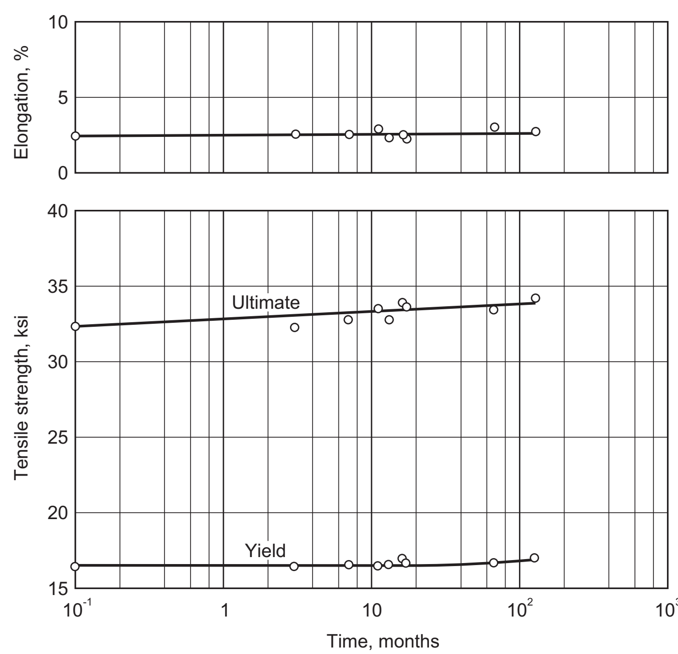

Fig. D1.40 Room-temperature aging characteristics for aluminum alloy 413.0-F, die cast

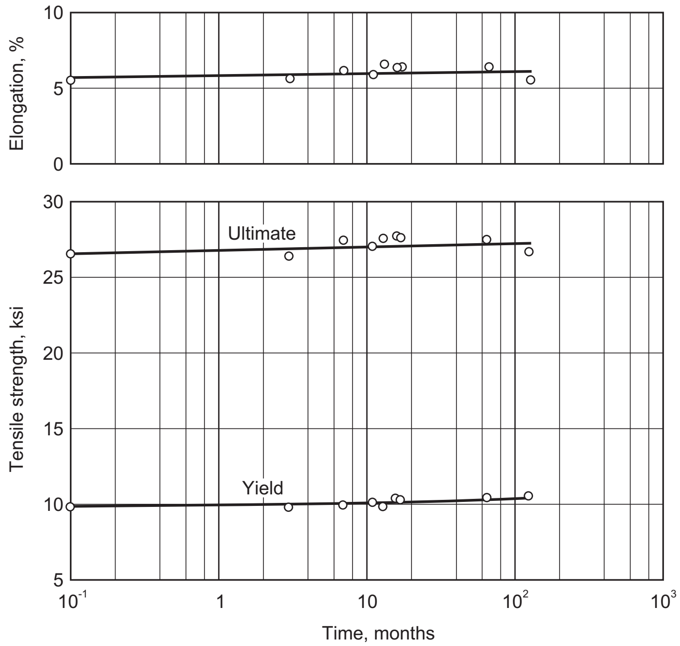

Fig. D1.41 Room-temperature aging characteristics for aluminum alloy 443.0-F, die cast

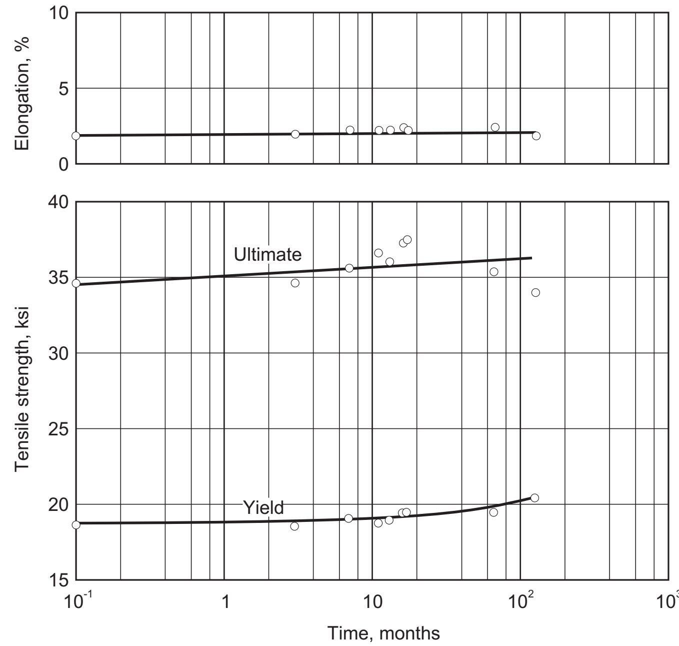

Fig. D1.42 Room-temperature aging characteristics for aluminum alloy C433.0-F, die cast. Long-term data, up to 125 months

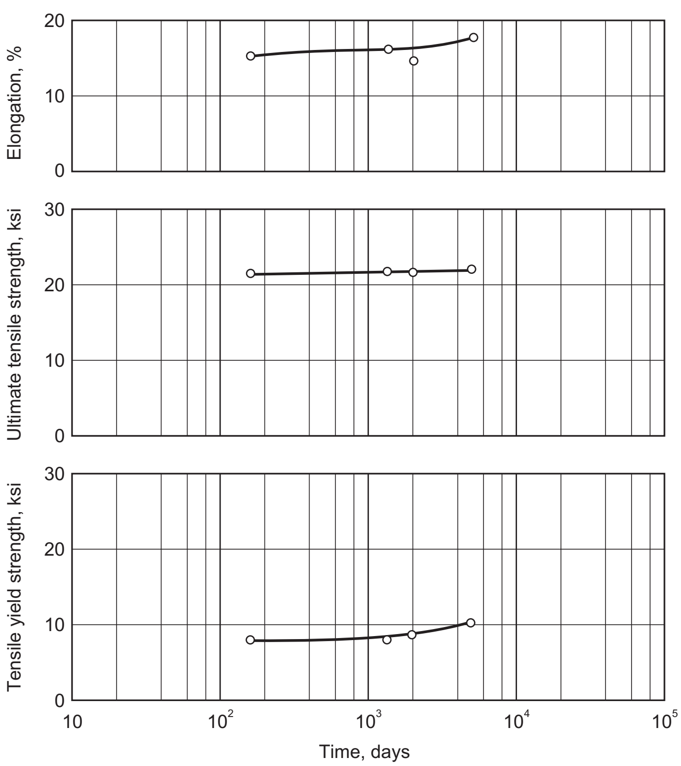

Fig. D1.43 Room-temperature aging characteristics for aluminum alloy C433.0-F, sand cast. Long-term data, up to 5000 days

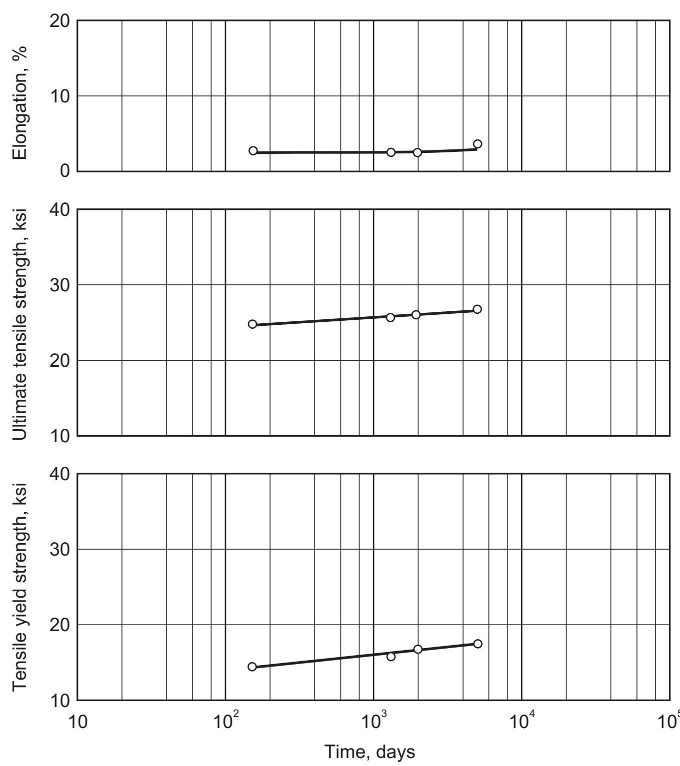

Fig. D1.44 Room-temperature aging characteristics for aluminum alloy 512.0-F, sand cast

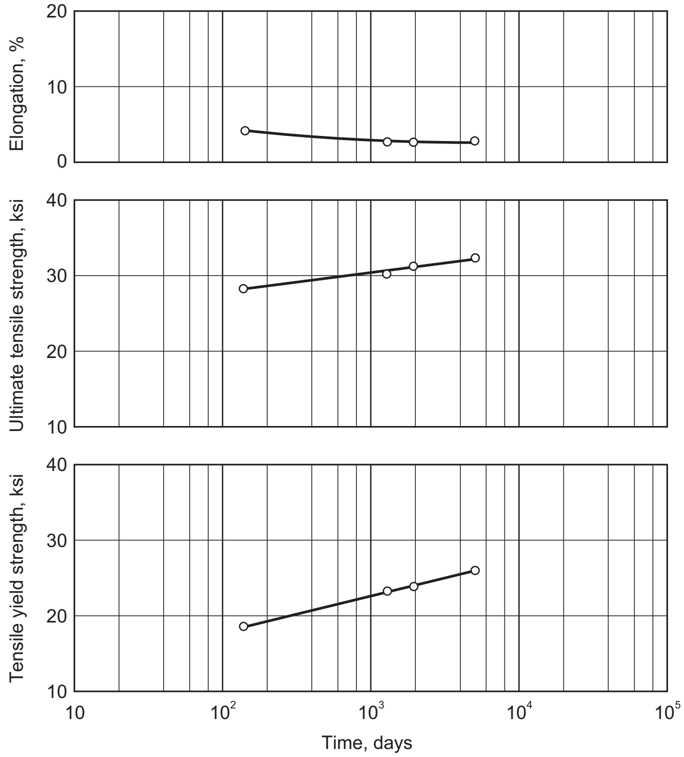

Fig. D1.45 Room-temperature aging characteristics for aluminum alloy 513.0-F, sand cast

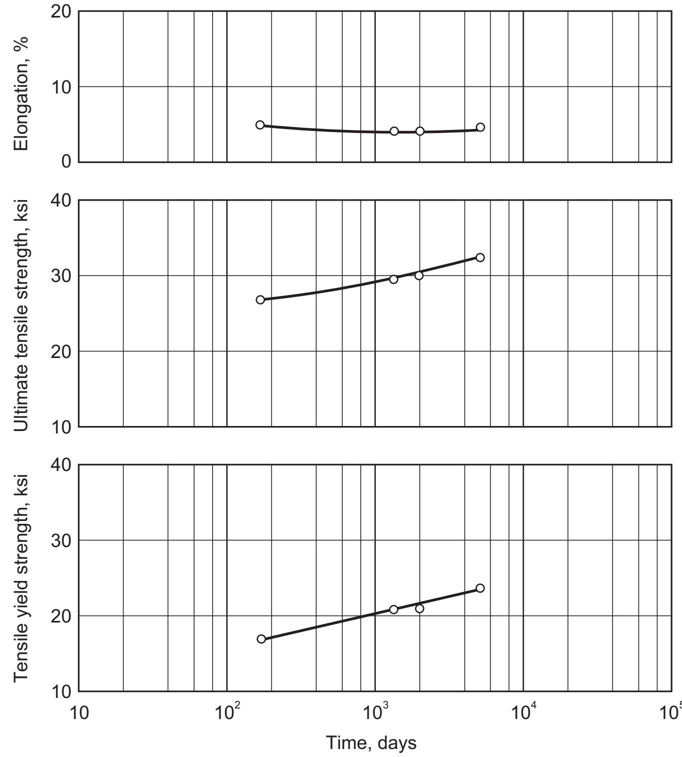

Fig. D1.46 Room-temperature aging characteristics for aluminum alloy 513.0-F, permanent mold

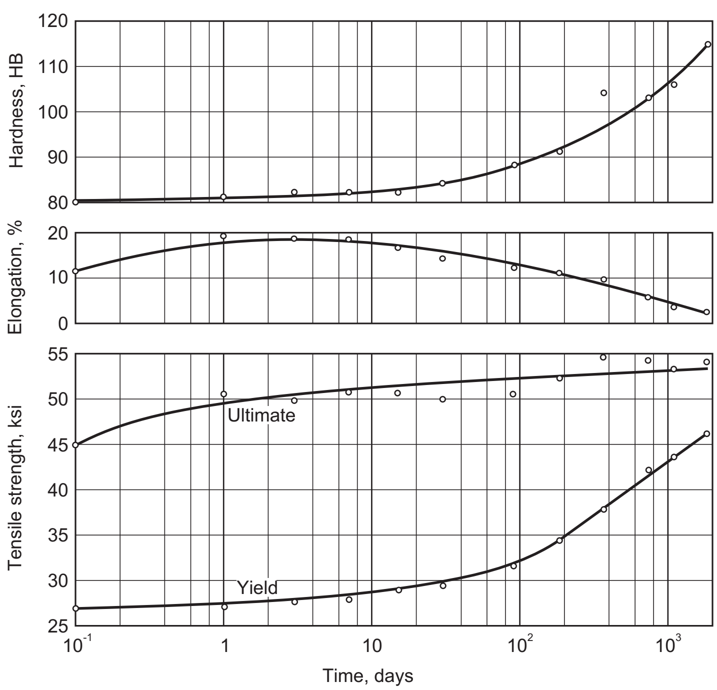

Fig. D1.47 Room-temperature aging characteristics for aluminum alloy 520.0-T4

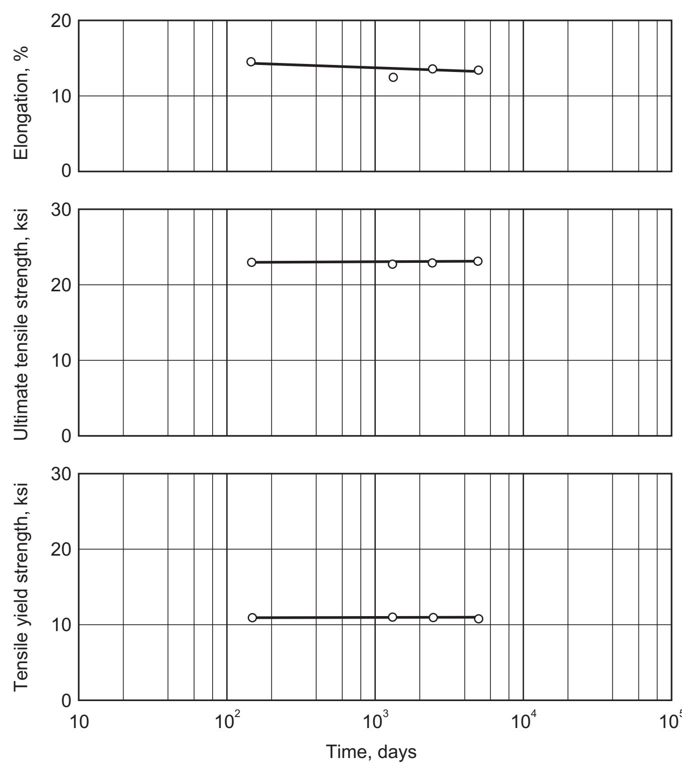

Fig. D1.48 Room-temperature aging characteristics for aluminum alloy 850.0-T5, permanent mold

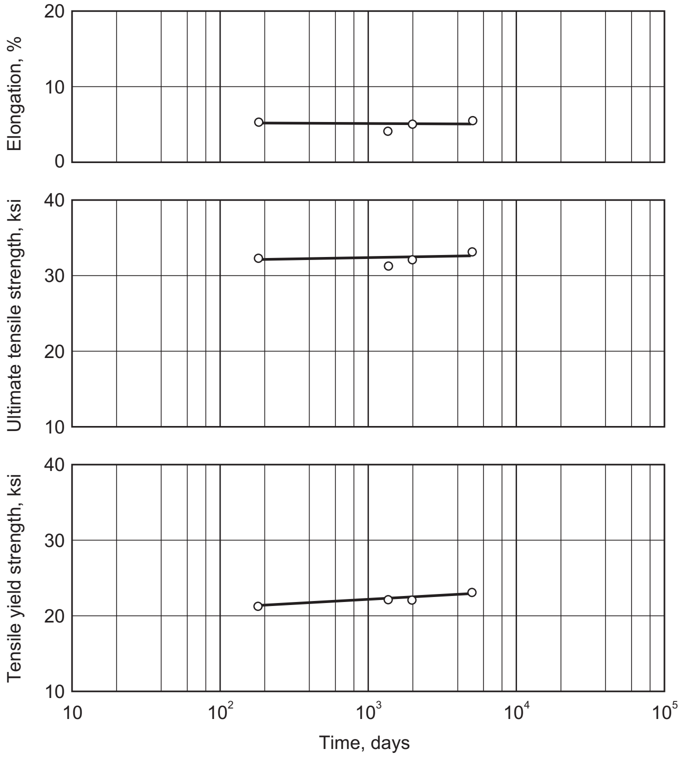

Fig. D1.49 Room-temperature aging characteristics for aluminum alloy 852.0-T5, permanent mold

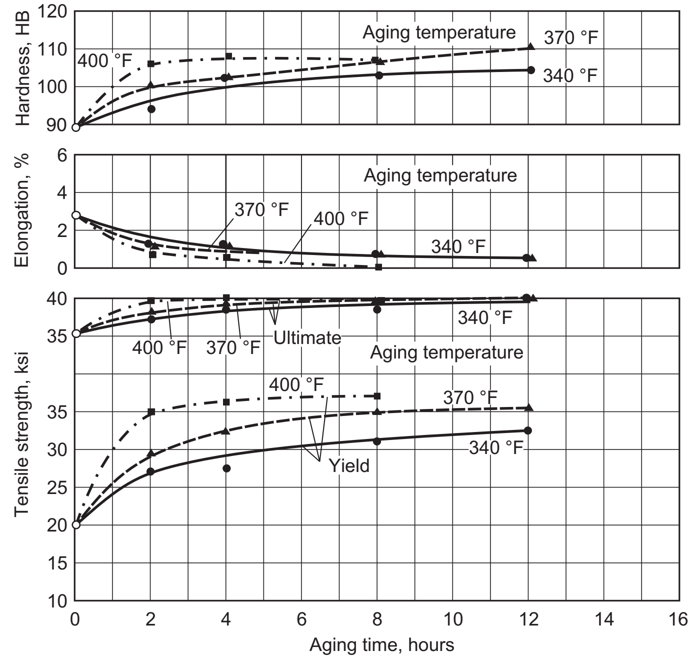

Fig. D1.50 High-temperature aging characteristics for aluminum alloy 242.0-F, permanent mold

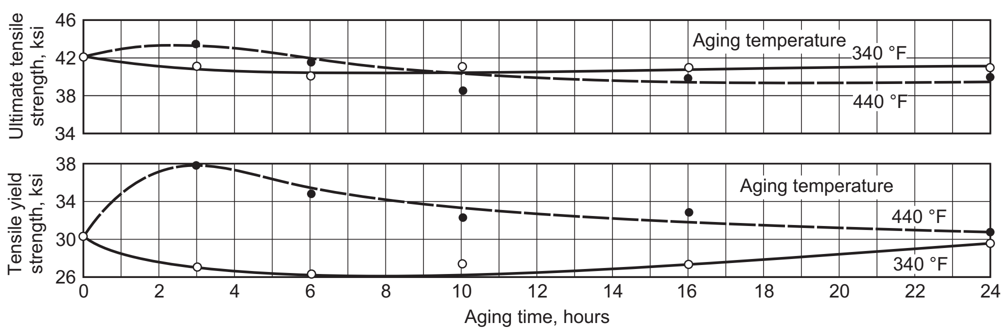

Fig. D1.51 High-temperature aging characteristics for aluminum alloy 242.0-F, permanent mold. Specimens were aged for 2 years at room temperature prior to aging at these temperatures.

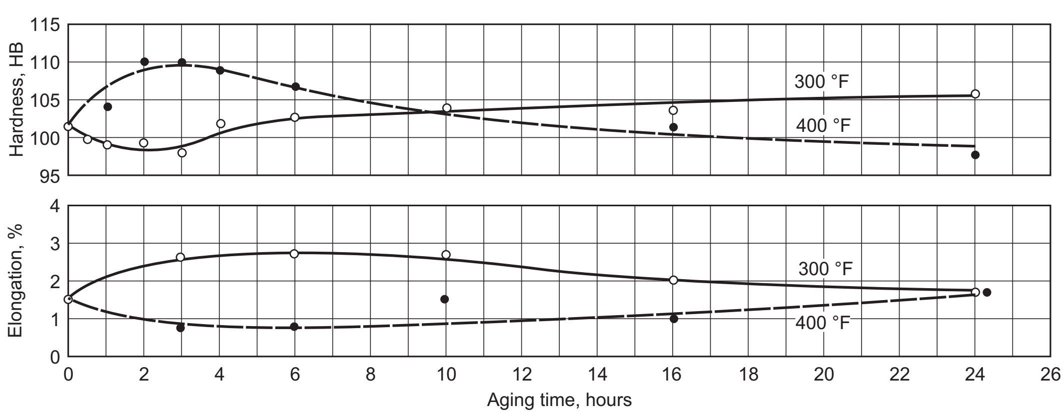

Fig. D1.52 High-temperature aging characteristics for aluminum alloy 242.0-F, permanent mold

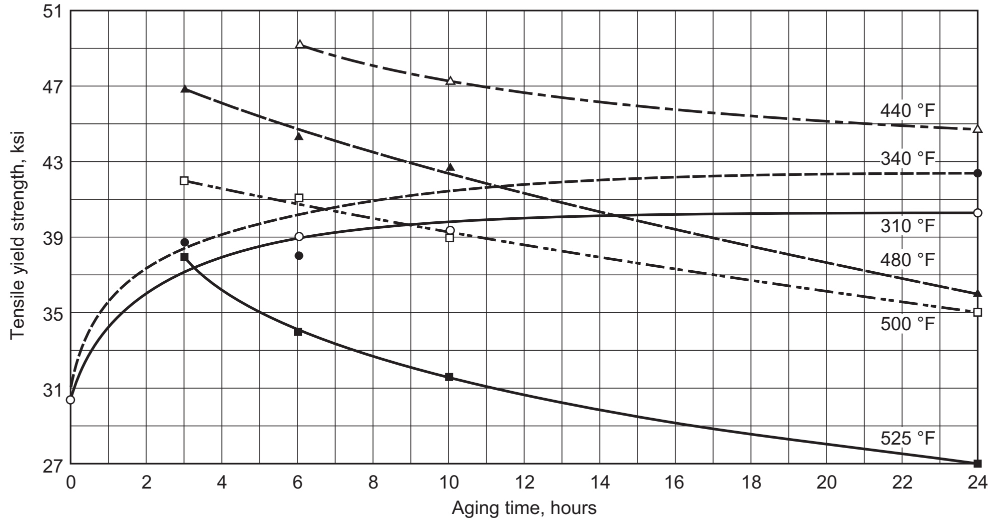

Fig. D1.53 High-temperature aging characteristics for aluminum alloy 242.0-T4, permanent mold. Solution heat treatment: 6 h at 960 °F, quenched in 110 °F water

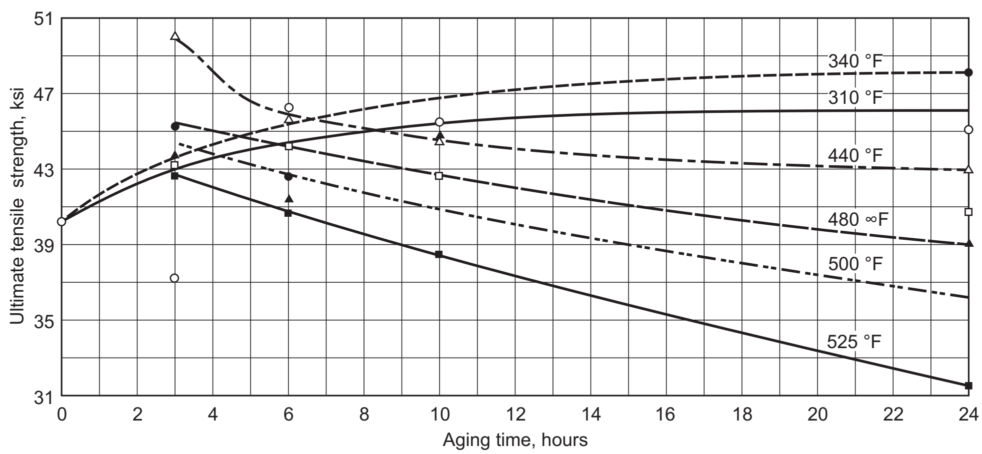

Fig. D1.54 High-temperature aging characteristics for aluminum alloy 242.0-T4, permanent mold. Solution heat treatment: 6 h at 960 °F, quenched in 110 °F water

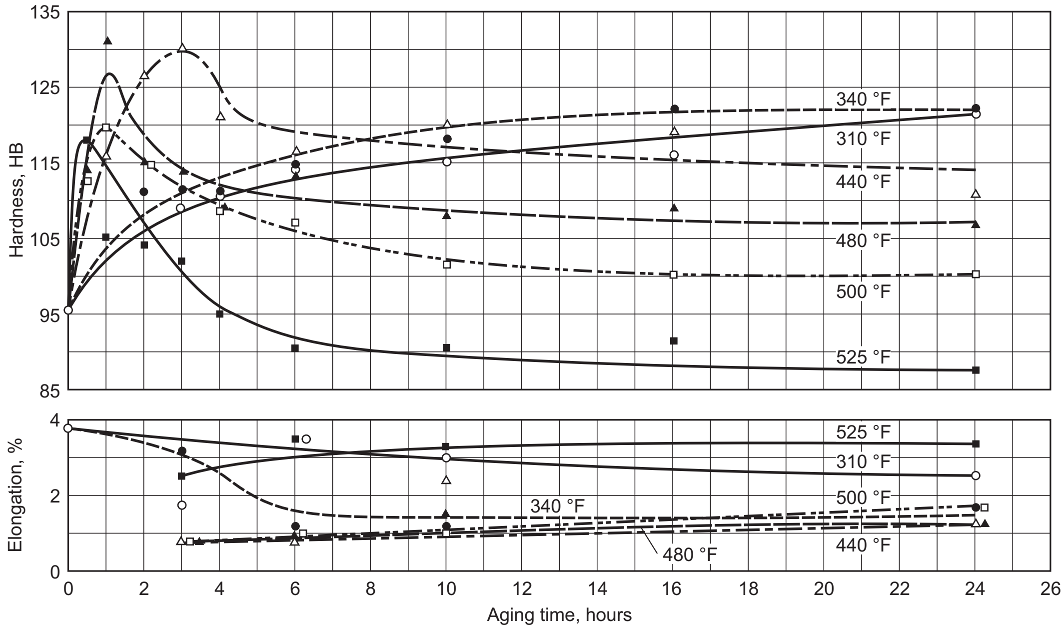

Fig. D1.55 High-temperature aging characteristics for aluminum alloy 242.0-T4, permanent mold. Solution heat treatment: 6 h at 960 °F, quenched in 110 °F water

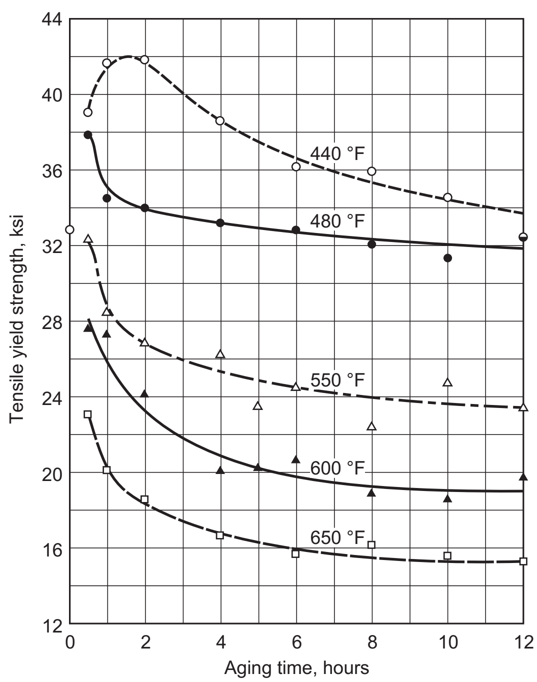

Fig. D1.56 High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Cooled in still air

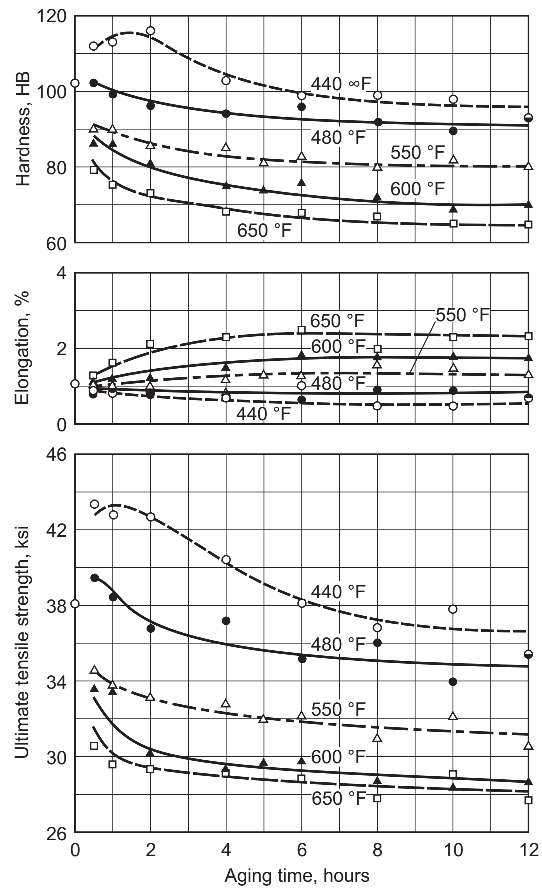

Fig. D1.57 High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Cooled in still air

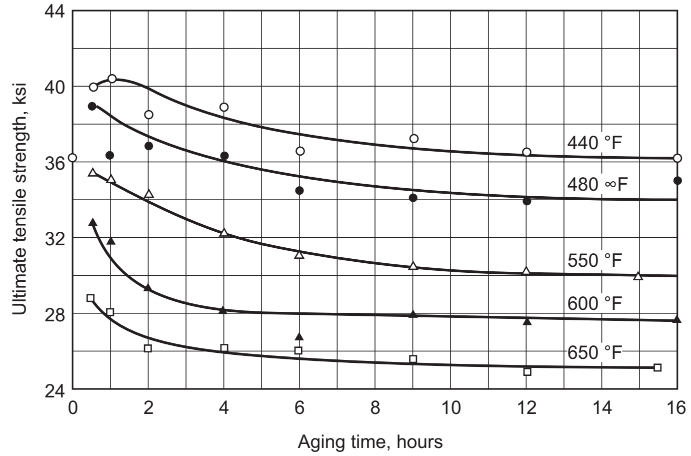

Fig. D1.58 High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Air blast quench

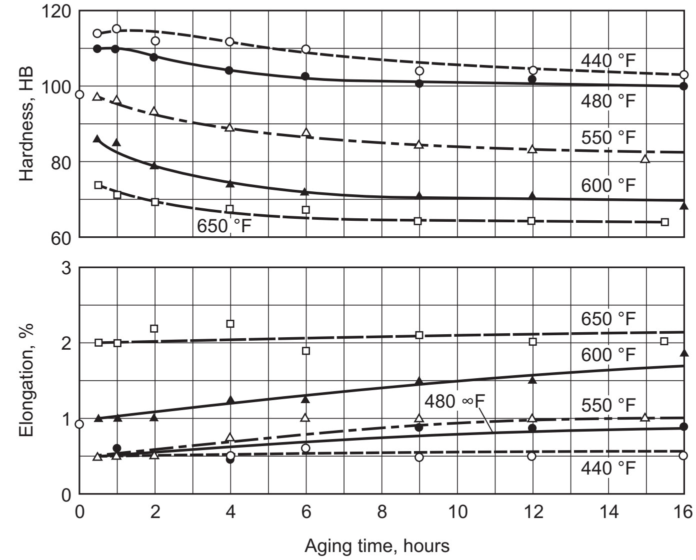

Fig. D1.59 High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Air blast quench

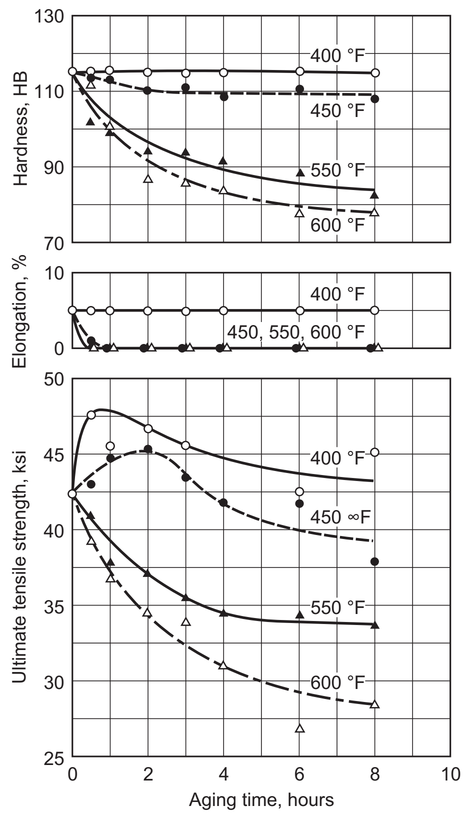

Fig. D1.60 High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Quenched in boiling water

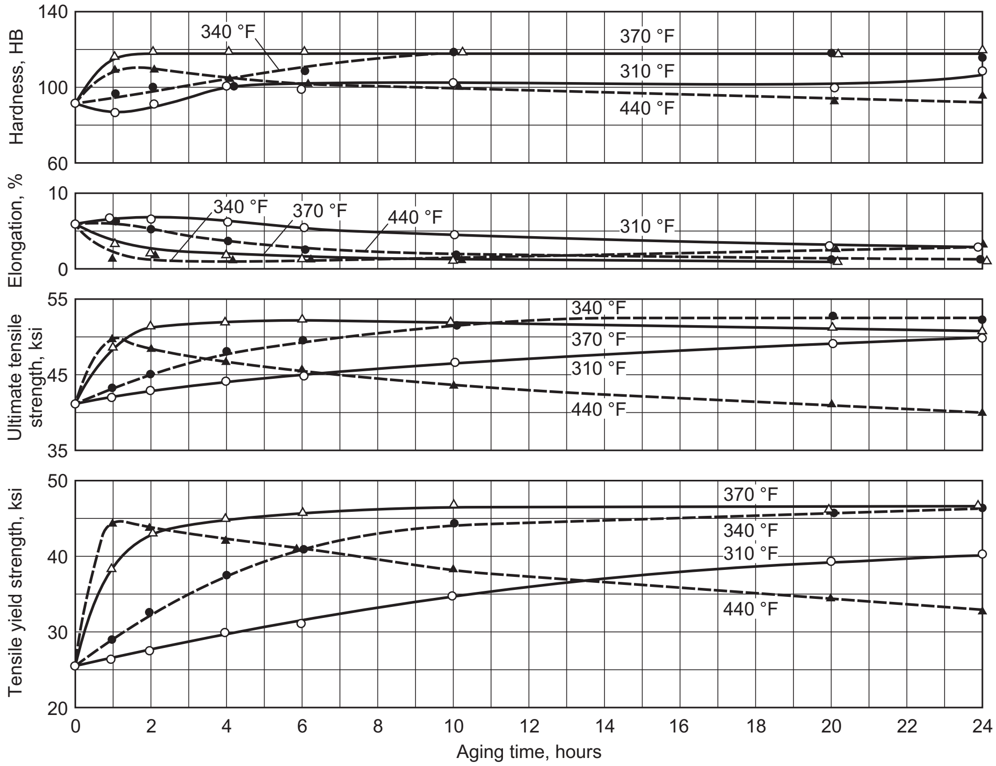

Fig. D1.61 High-temperature aging characteristics for aluminum alloy C355.0-T4, sand cast. Solution heat treated 15 h at 980 °F, quenched in water at 150 °F. 24 h interval at room temperature. Heat-up times to the aging temperatures varied from 1 h 5 min to 1 h 45 min.

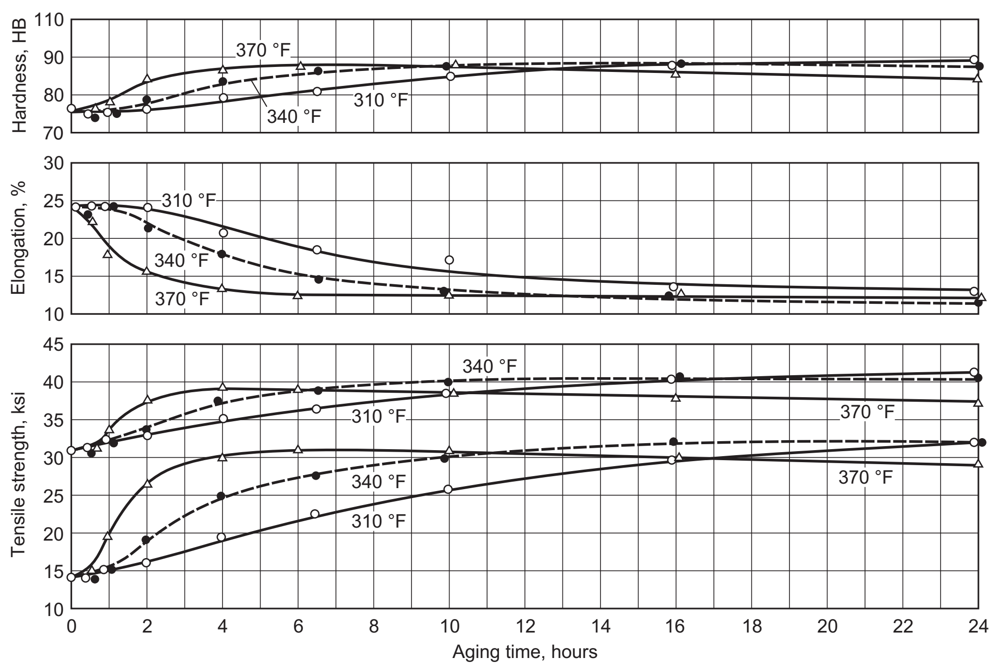

Fig. D1.62 High-temperature aging characteristics for aluminum alloy A356.0-T4, permanent mold. Solution heat treated 15 h at 1000 °F, quenched in boiling water. 24 h interval at room temperature

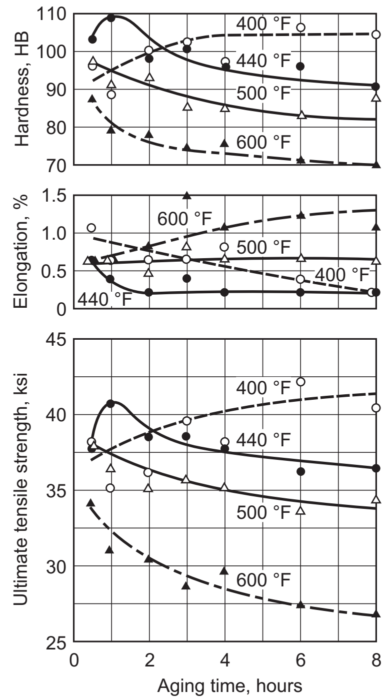

Fig. D1.63 High-temperature aging characteristics for aluminum alloy A242.0-T4, sand cast. Quenched in boiling water

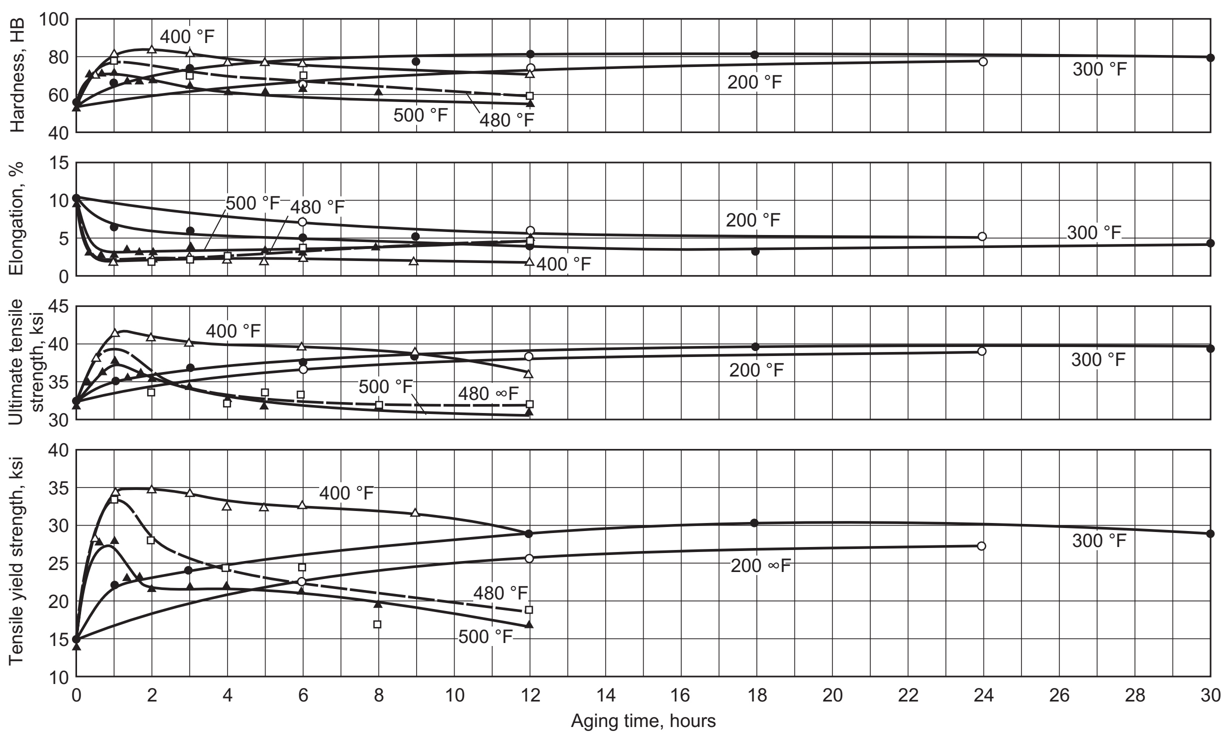

Fig. D1.64 High-temperature aging characteristics for aluminum alloy 295.0-T4, sand cast

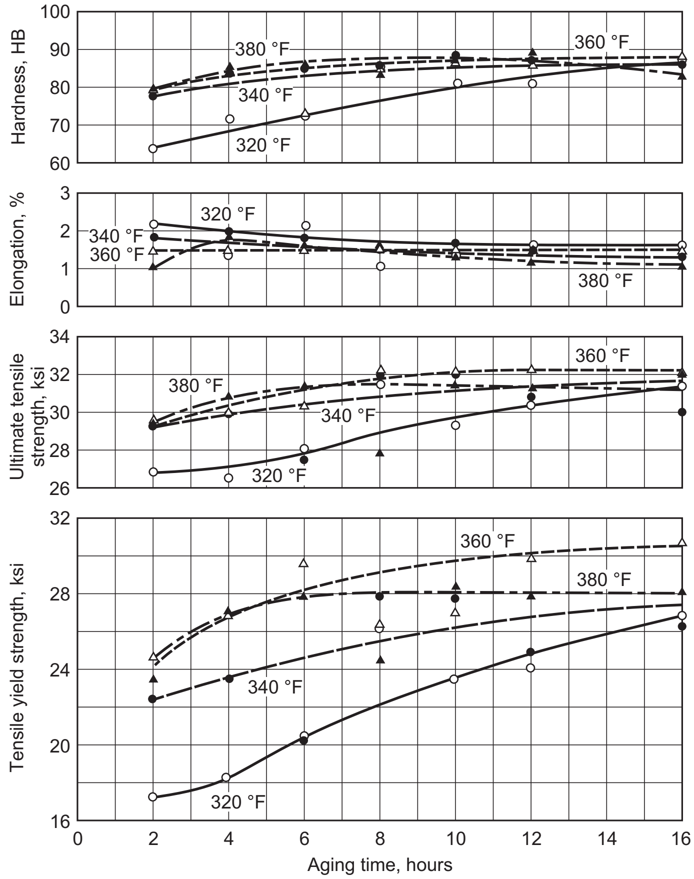

Fig. D1.65 High-temperature aging characteristics for aluminum alloy 319.0-F, sand cast

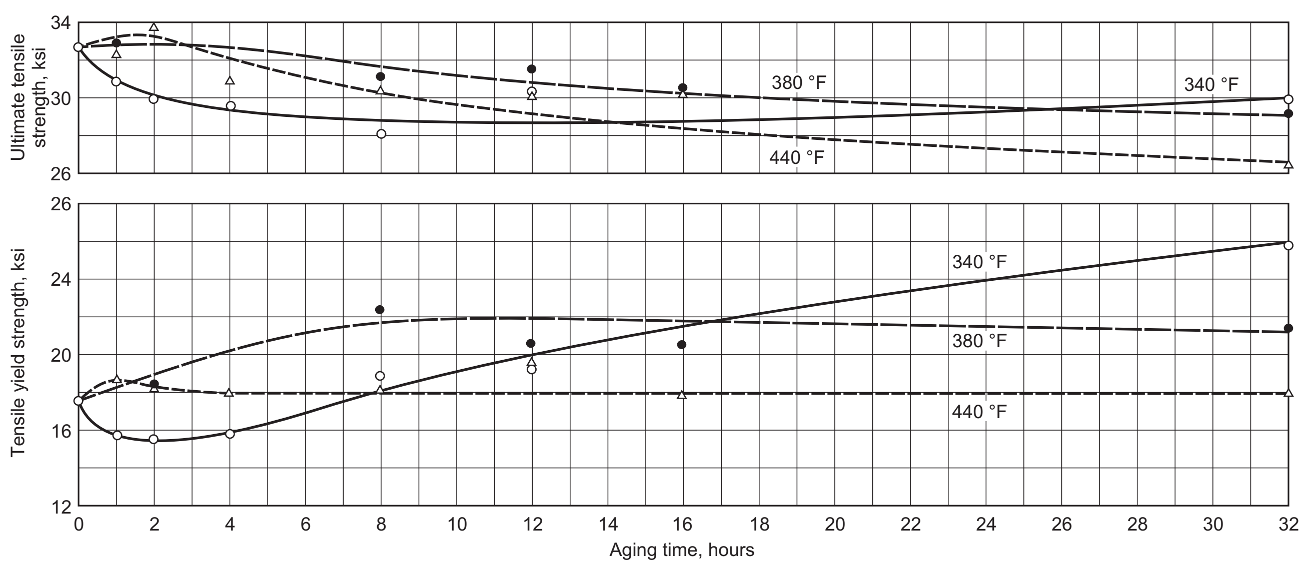

Fig. D1.66 High-temperature aging characteristics for aluminum alloy 319.0-F, permanent mold

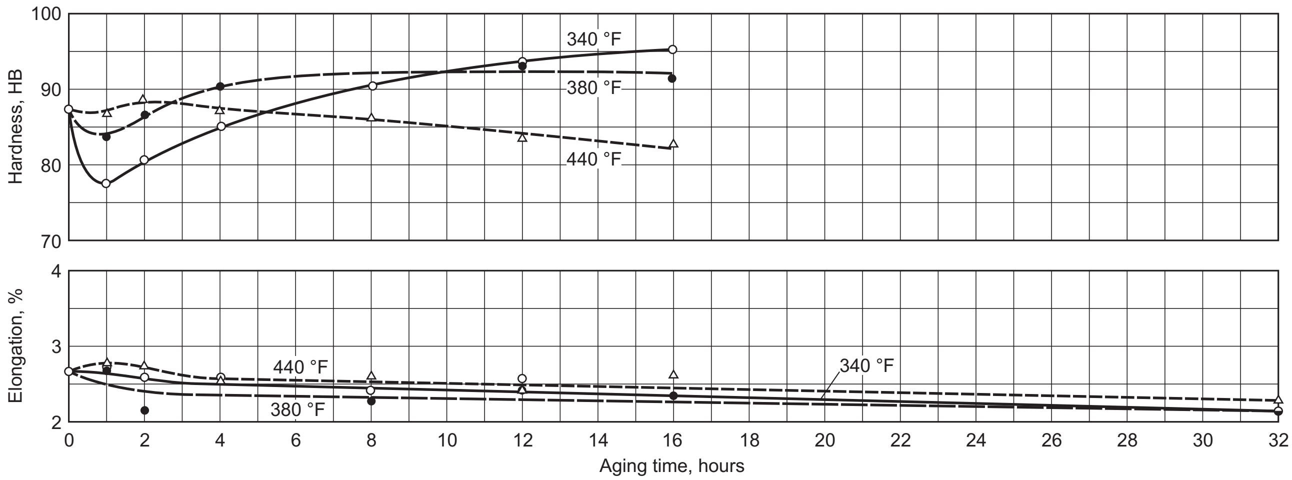

Fig. D1.67 High-temperature aging characteristics for aluminum alloy 319.0-F, permanent mold

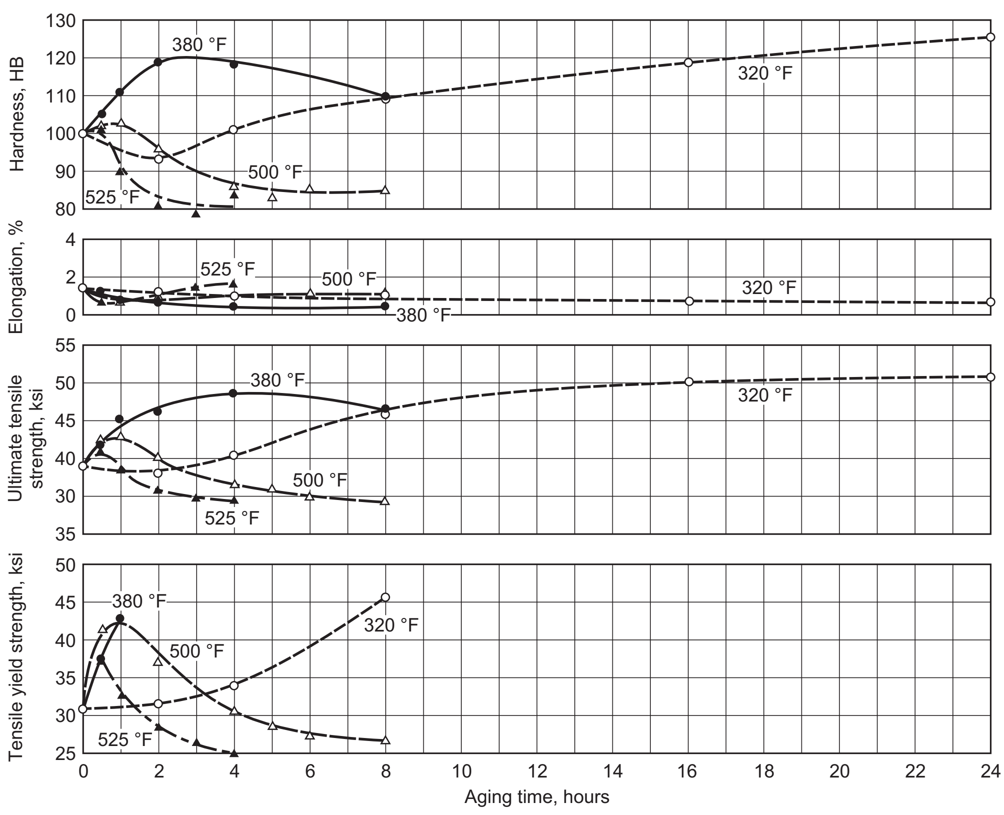

Fig. D1.68 High-temperature aging characteristics for aluminum alloy 319.0-F, sand cast. Aged 10 days at room temperature. Solution heat treated 12 h at 940 °F, quenched in boiling water

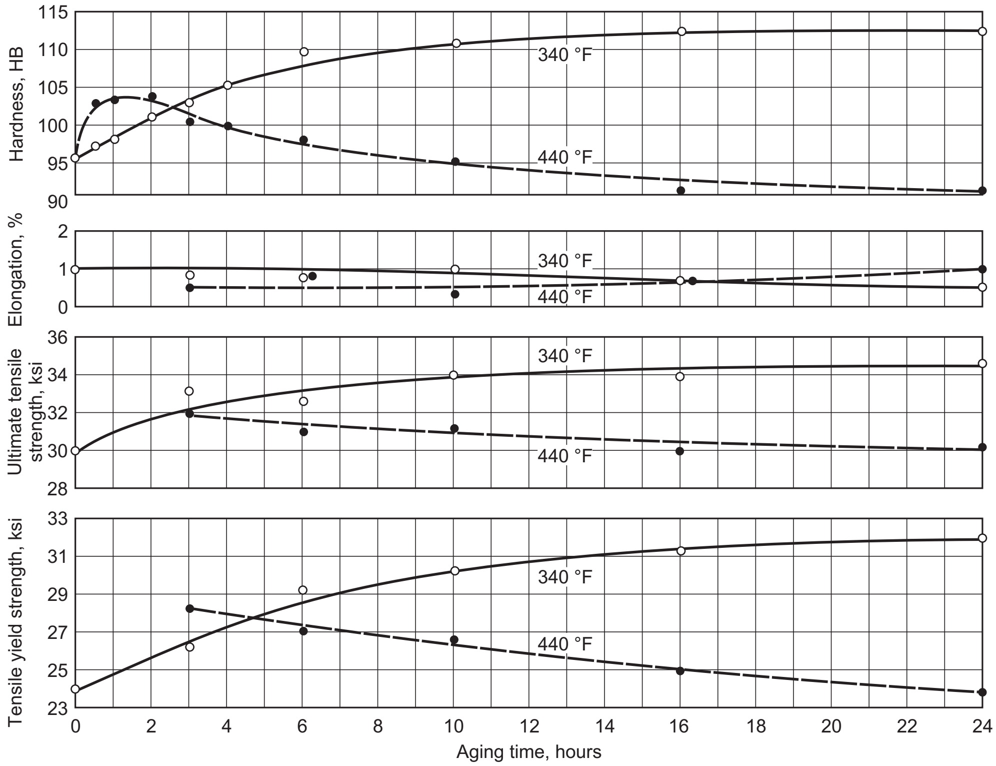

Fig. D1.69 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

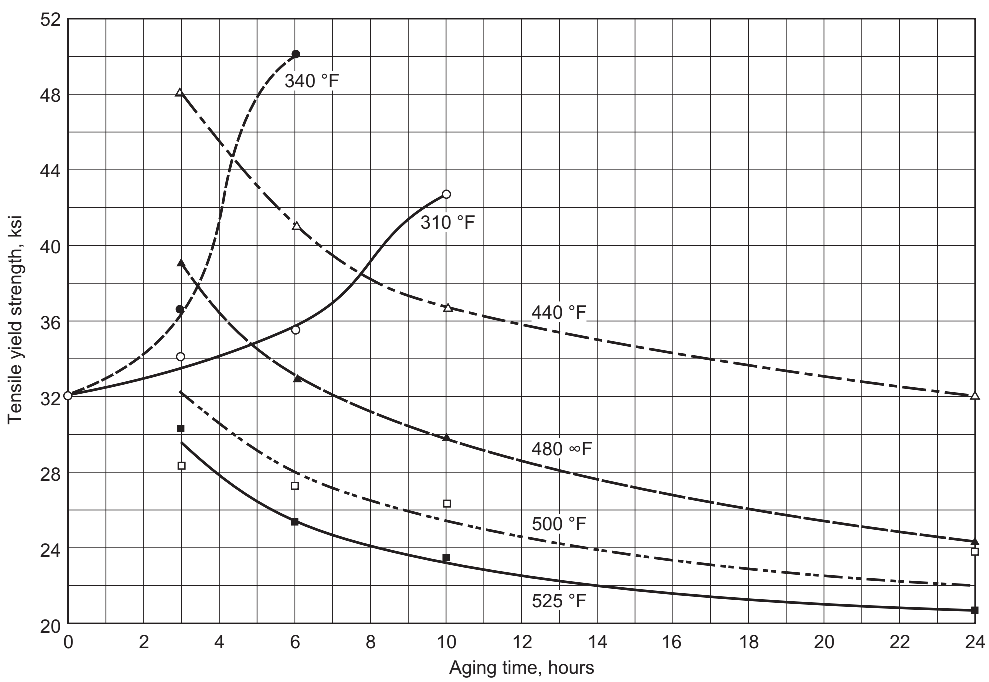

Fig. D1.70 High-temperature aging characteristics for aluminum alloy 333.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

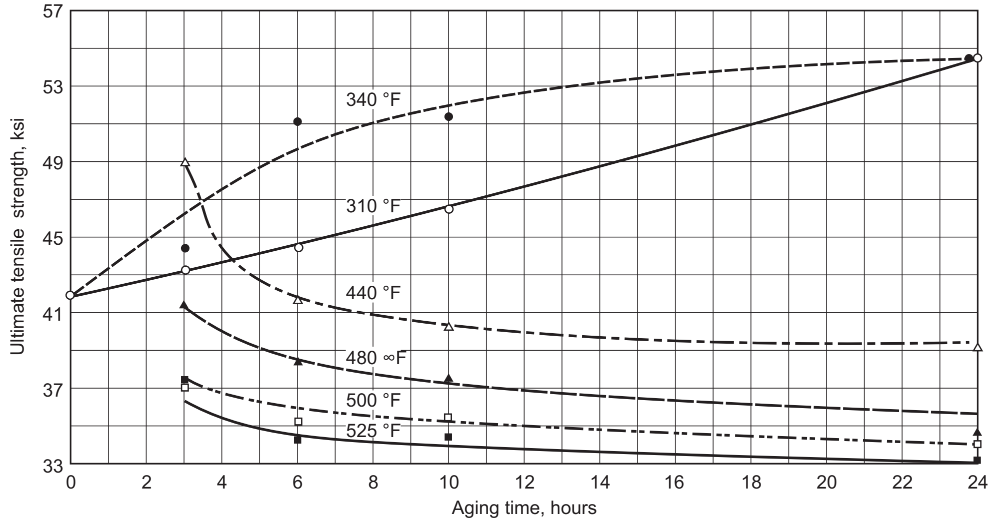

Fig. D1.71 High-temperature aging characteristics for aluminum alloy 333.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

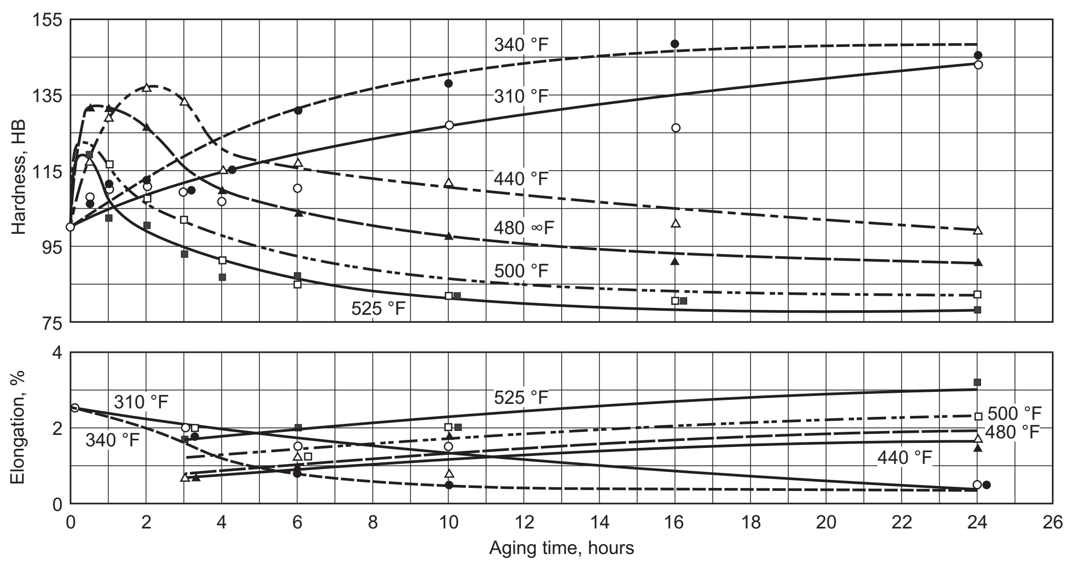

Fig. D1.72 High-temperature aging characteristics for aluminum alloy 333.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

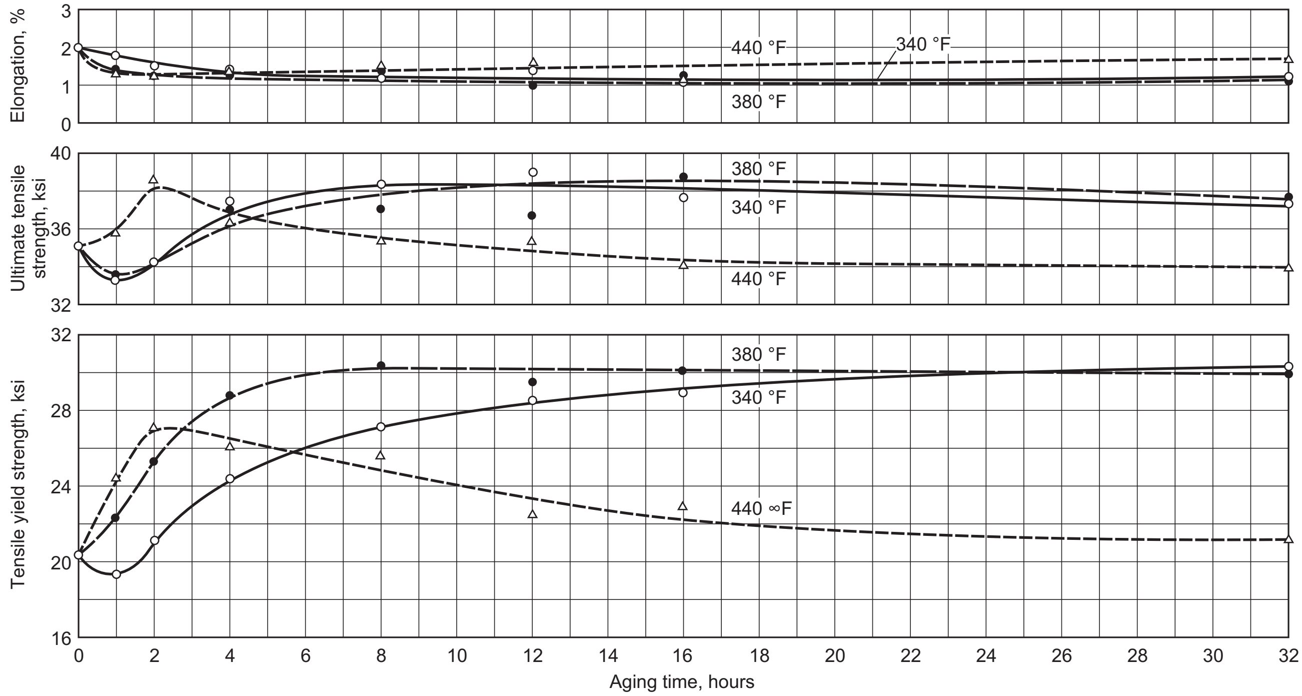

Fig. D1.73 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

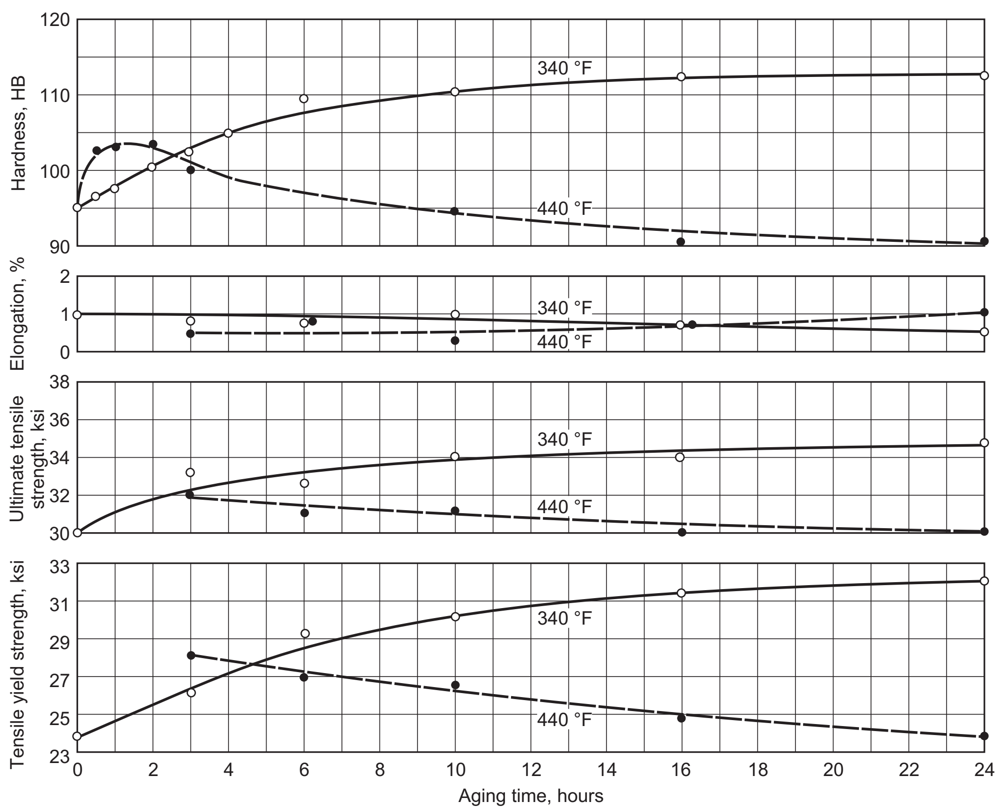

Fig. D1.74 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

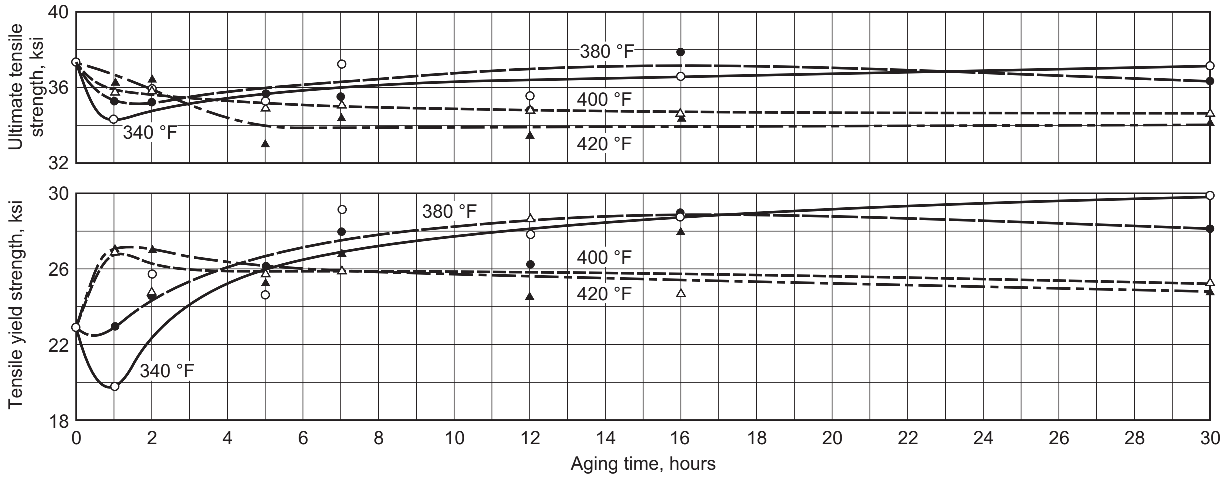

Fig. D1.75 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

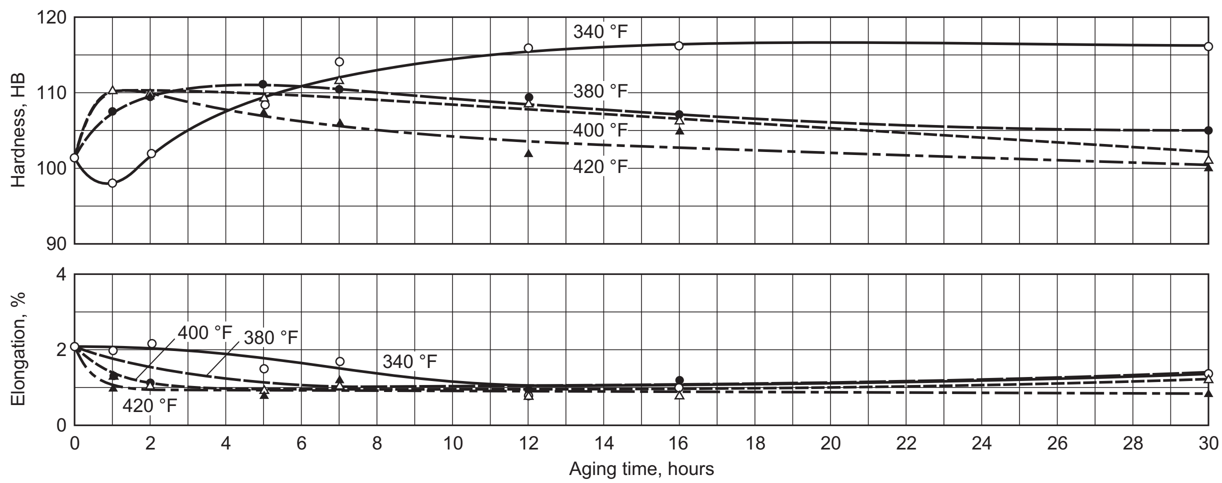

Fig. D1.76 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

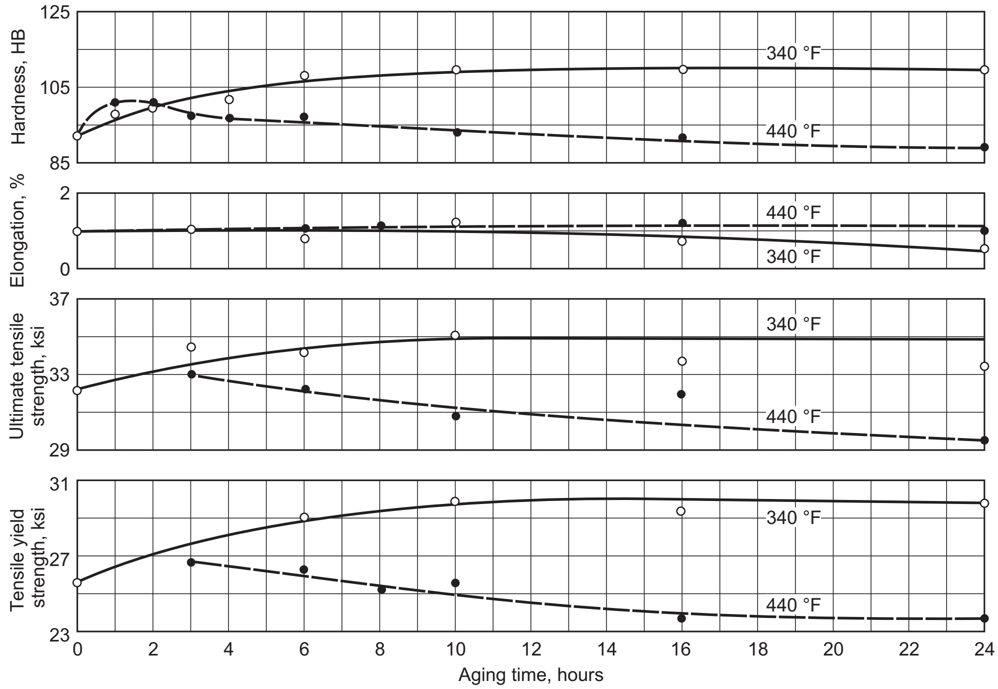

Fig. D1.77 High-temperature aging characteristics for aluminum alloy 336.0-F, permanent mold

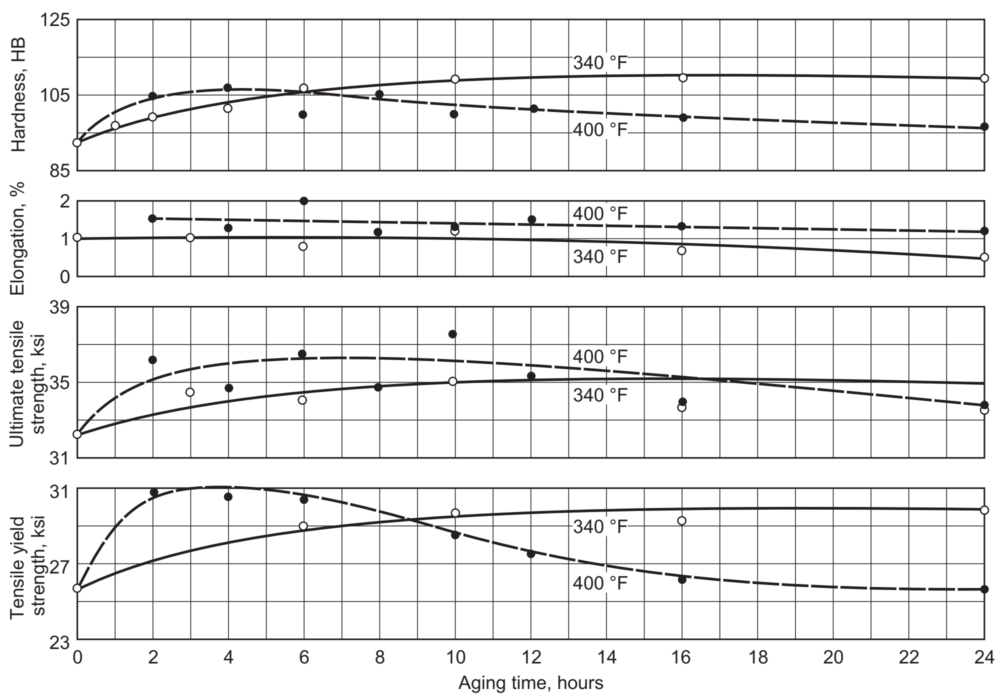

Fig. D1.78 High-temperature aging characteristics for aluminum alloy 336.0-F, permanent mold

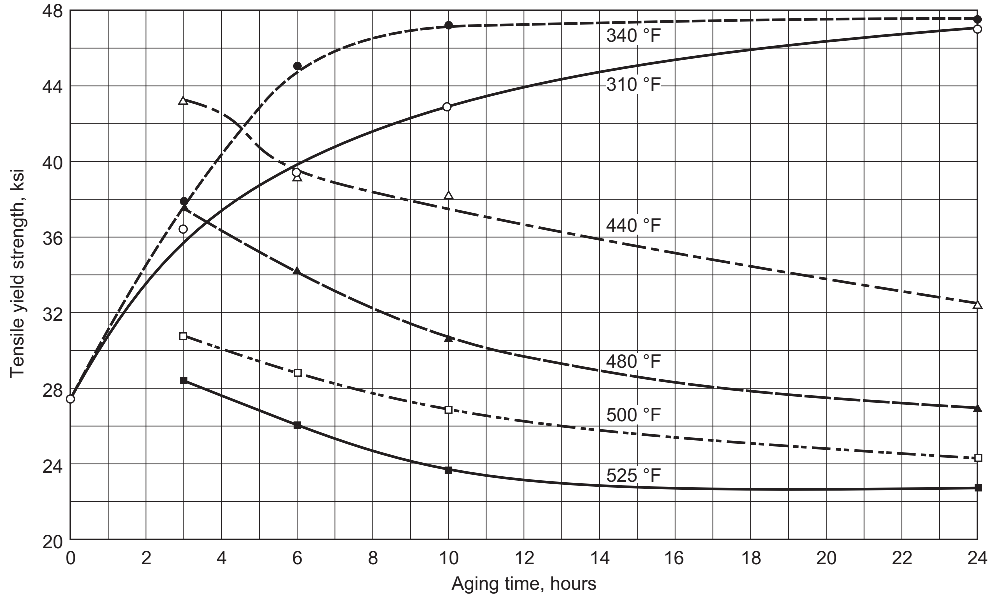

Fig. D1.79 High-temperature aging characteristics for aluminum alloy 336.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

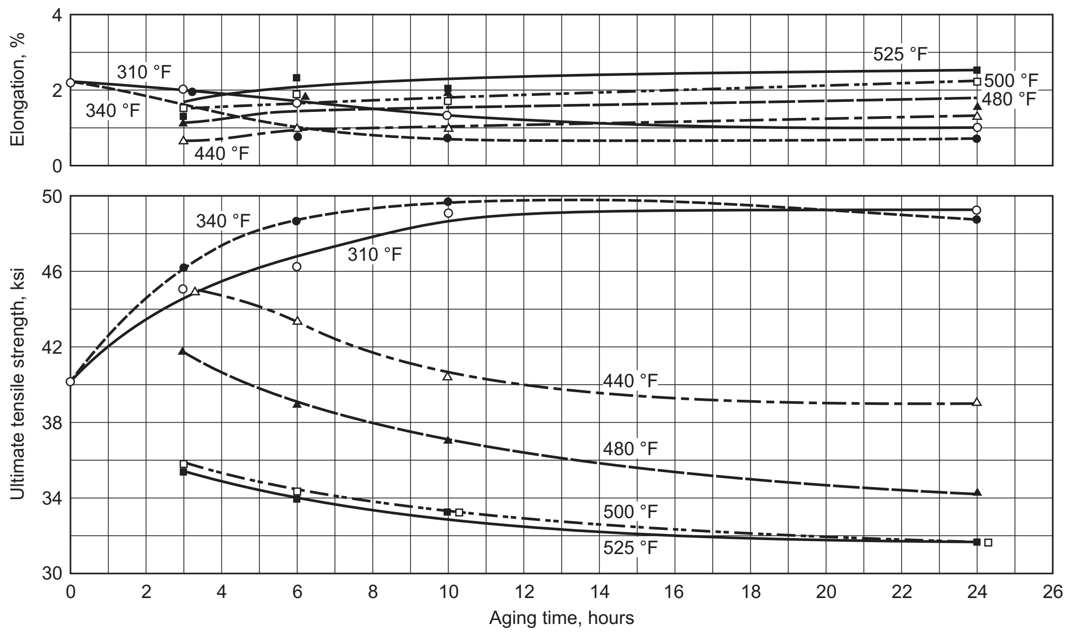

Fig. D1.80 High-temperature aging characteristics for aluminum alloy 336.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

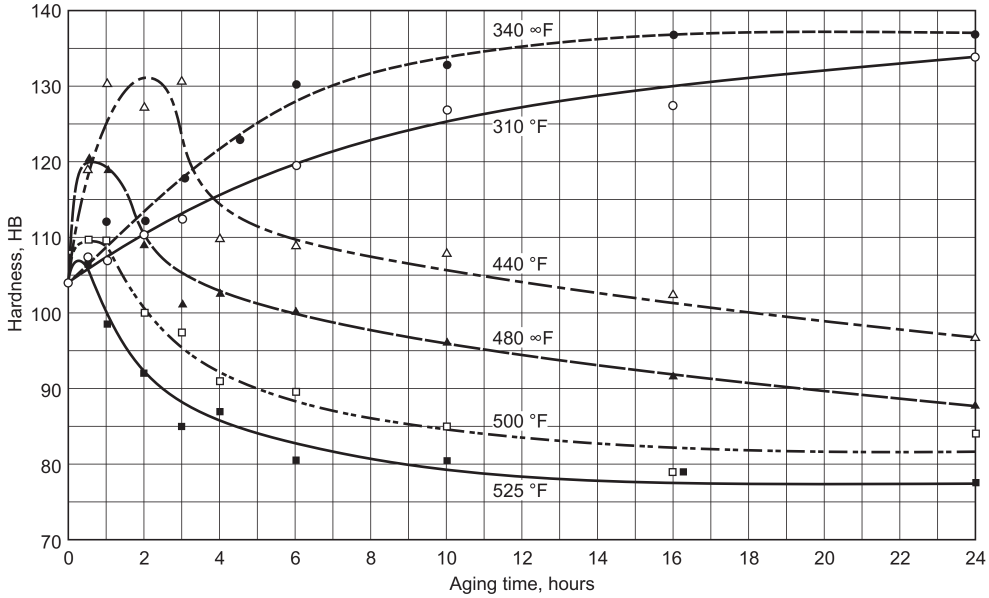

Fig. D1.81 High-temperature aging characteristics for aluminum alloy 336.0-T4, permanent mold. Solution heat treated 6 h at 960 ºF, quenched in water at 110 ºF

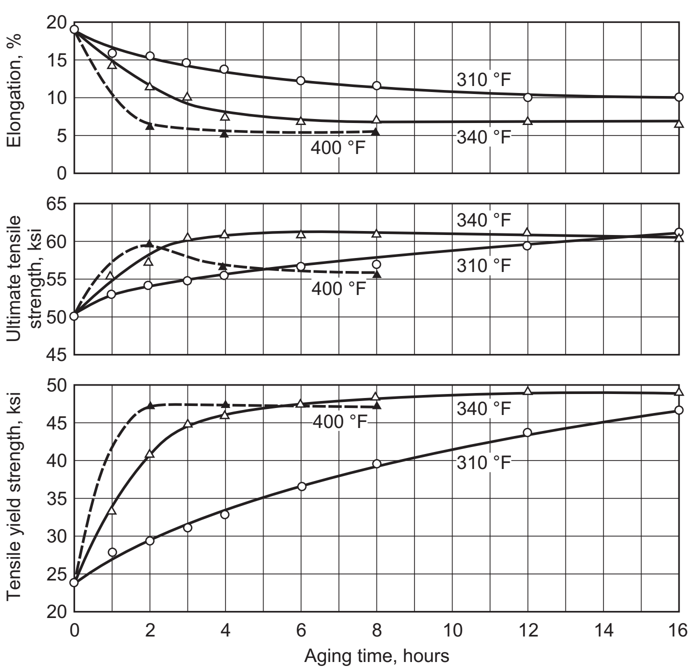

Fig. D1.82 High-temperature aging characteristics for aluminum alloy 354.0-T4, permanent mold. Solution heat treated 8 h at 980 ºF, quenched in room temperature water. Held 4 h at room temperature

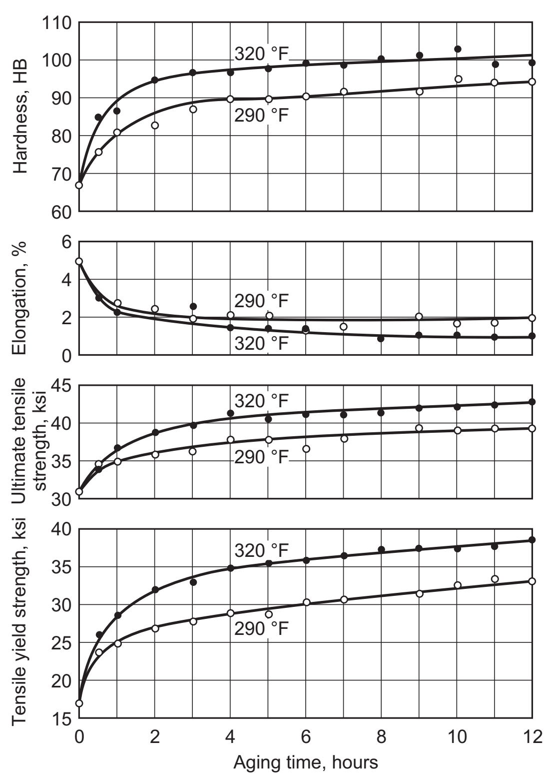

Fig. D1.83 High-temperature aging characteristics for aluminum alloy 355.0-T4, sand cast

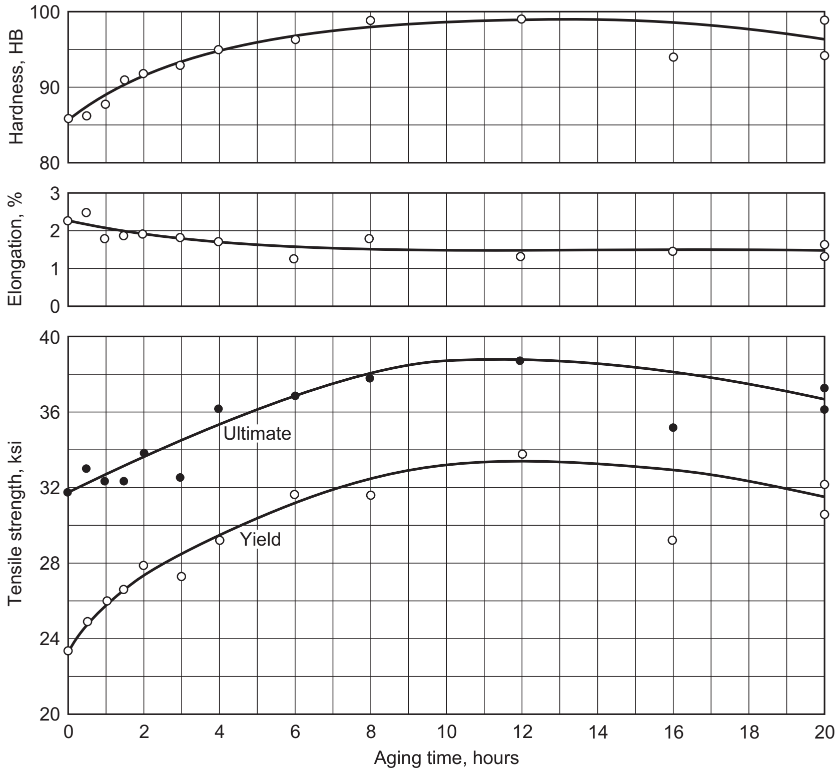

Fig. D1.84 High-temperature aging characteristics for aluminum alloy 355.0-T4, sand cast. Aging at 275 °F with boiling water quench

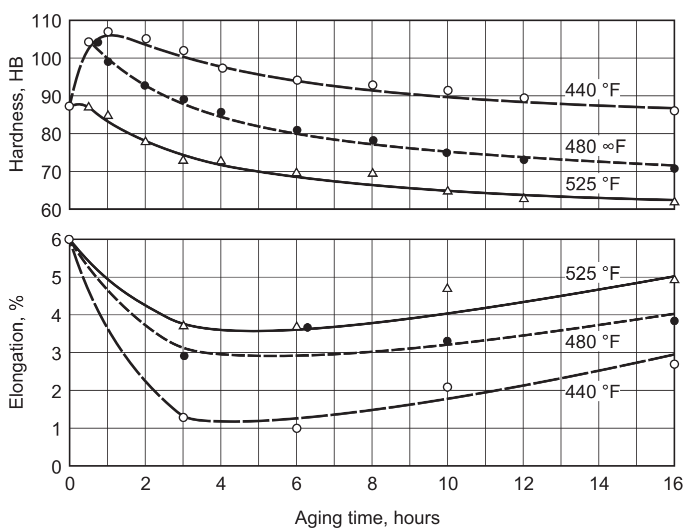

Fig. D1.85 High-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

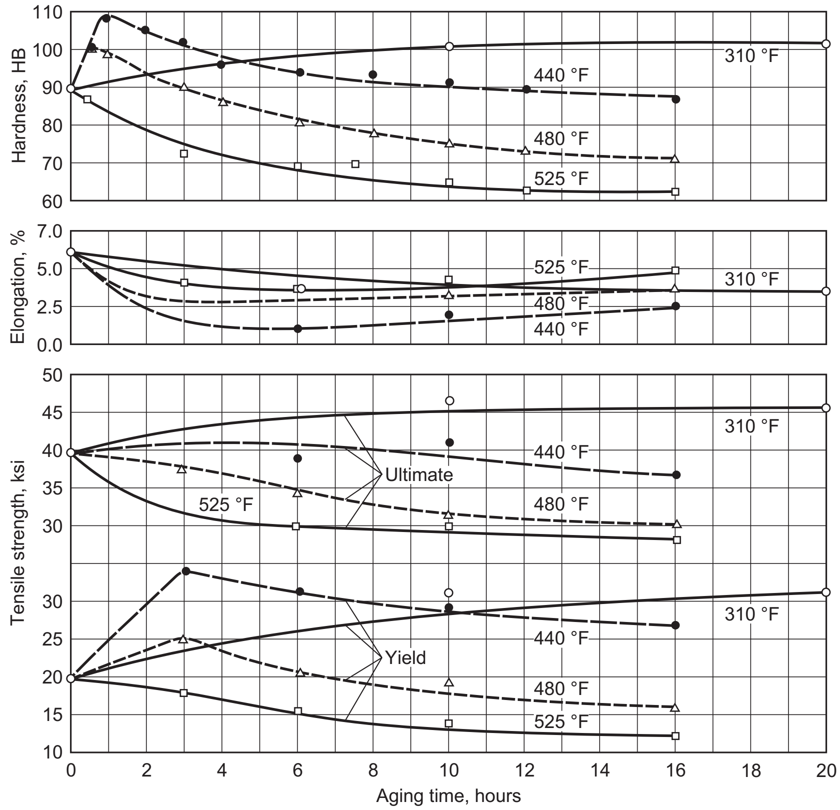

Fig. D1.86 High-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

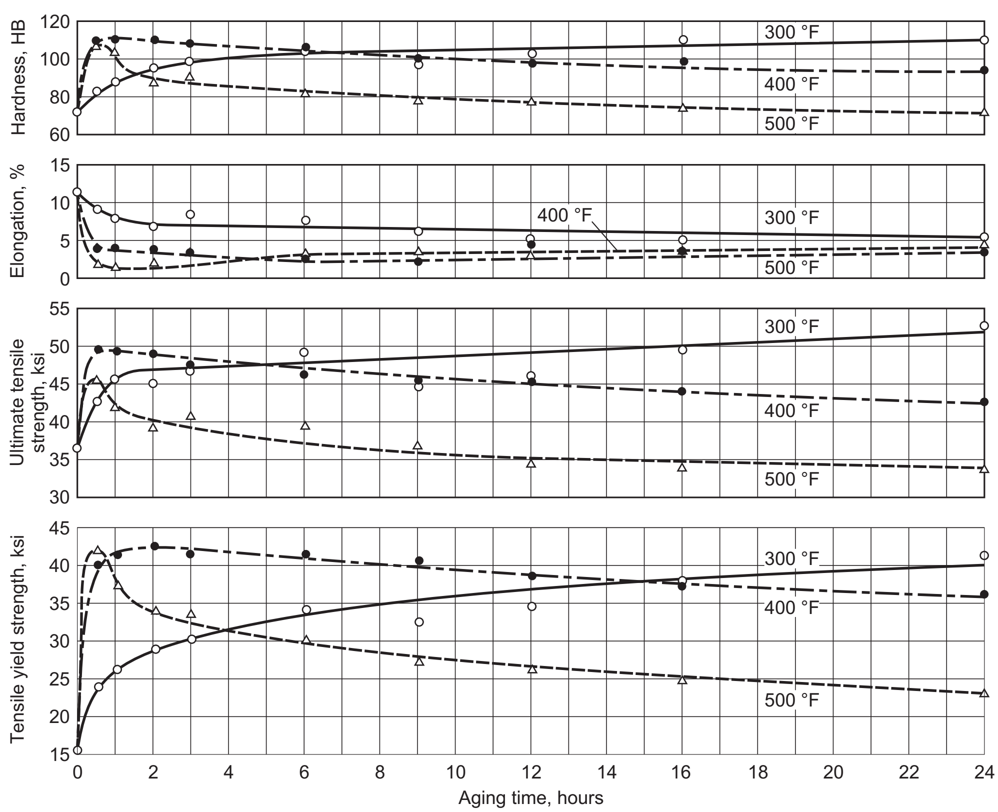

Fig. D1.87 High-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

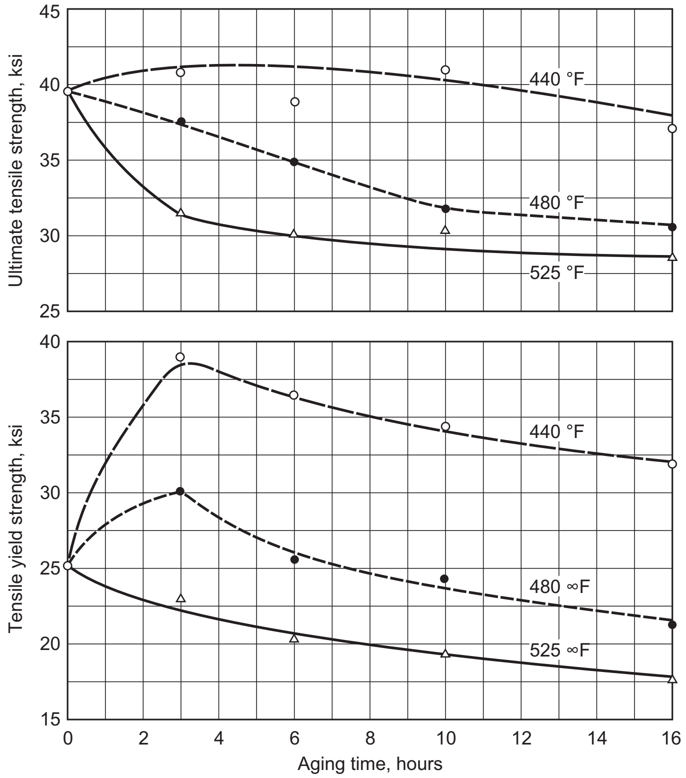

Fig. D1.88 High-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

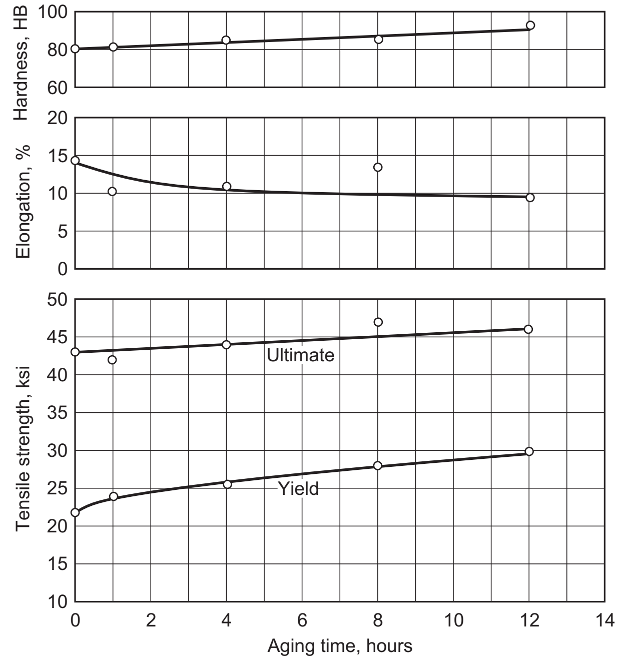

Fig. D1.89 High-temperature aging characteristics for aluminum alloy C355.0-T4, permanent mold. Solution heat treated 8 h at 980 °F, quenched in 200 °F water. Held 16 h at room temperature. Aged at 310 °F

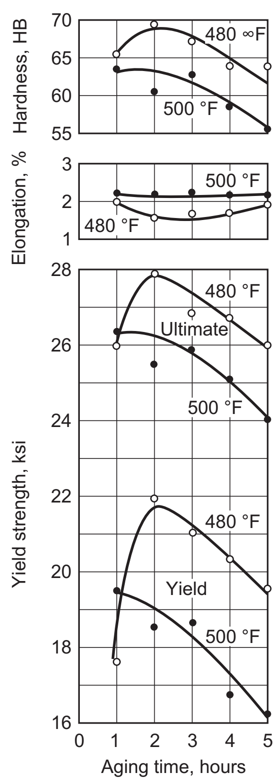

Fig. D1.90 High-temperature aging characteristics for aluminum alloy 356.0-F, sand cast

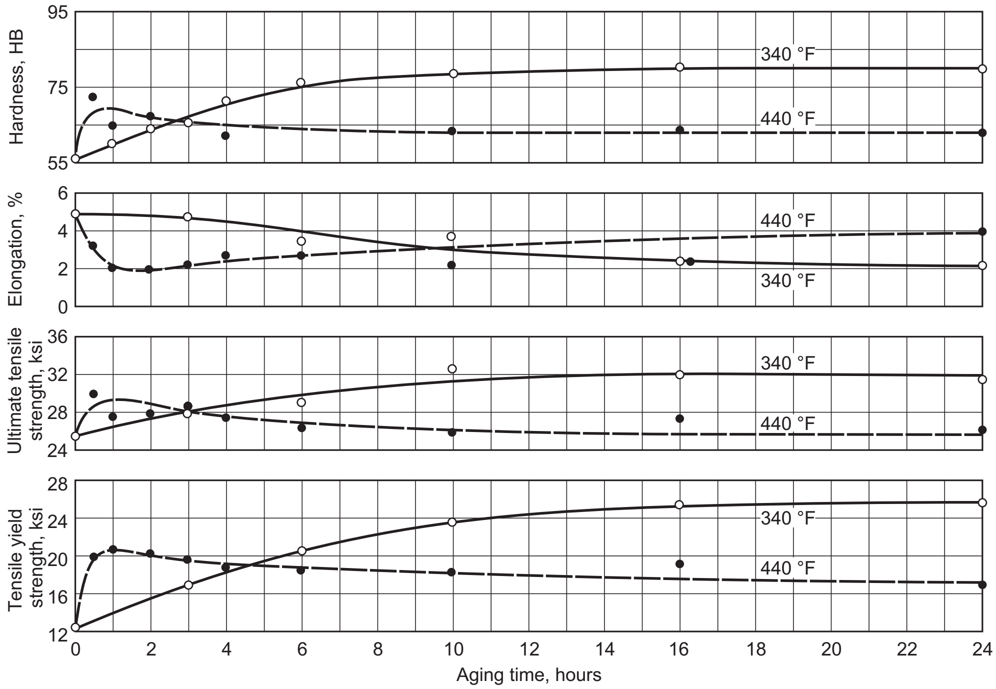

Fig. D1.91 High-temperature aging characteristics for aluminum alloy 356.0-F, permanent mold

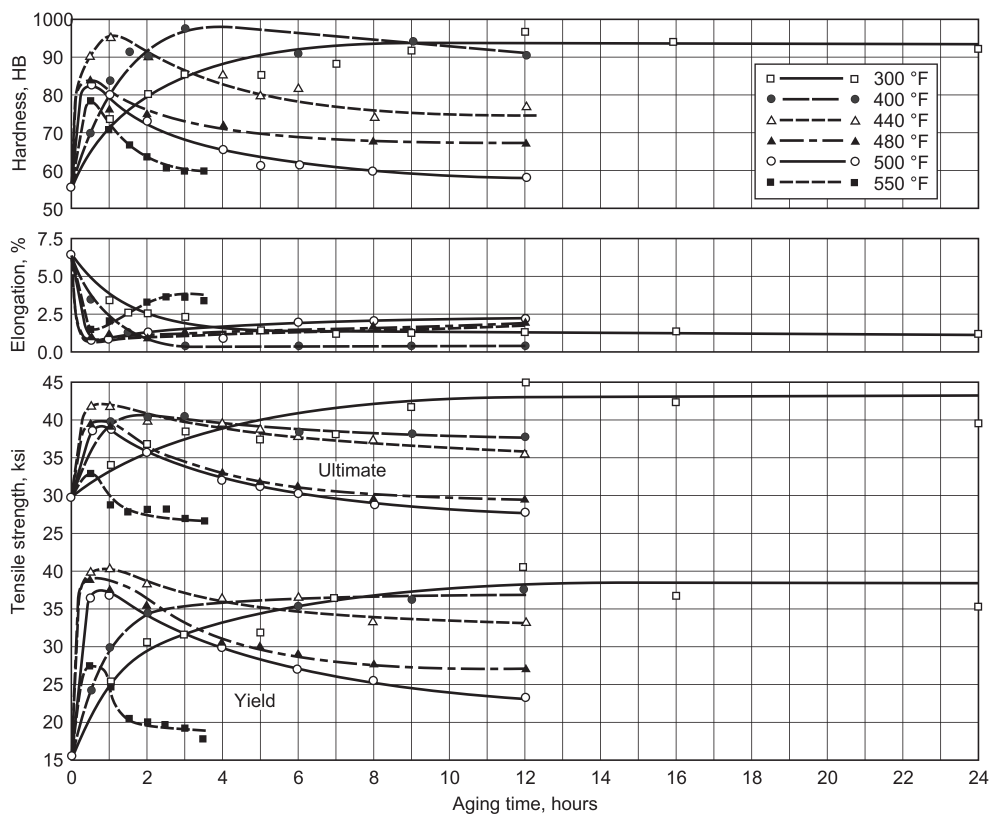

Fig. D1.92 High-temperature aging characteristics for aluminum alloy 356.0-T4, sand cast

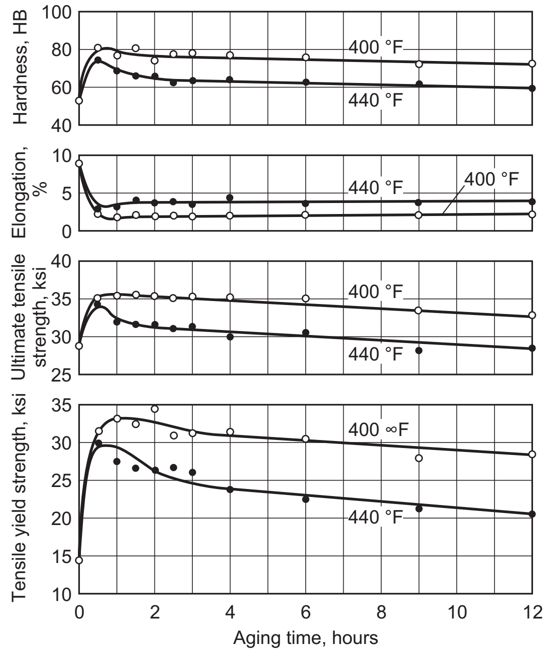

Fig. D1.93 High-temperature aging characteristics for aluminum alloy 356.0-T4, sand cast

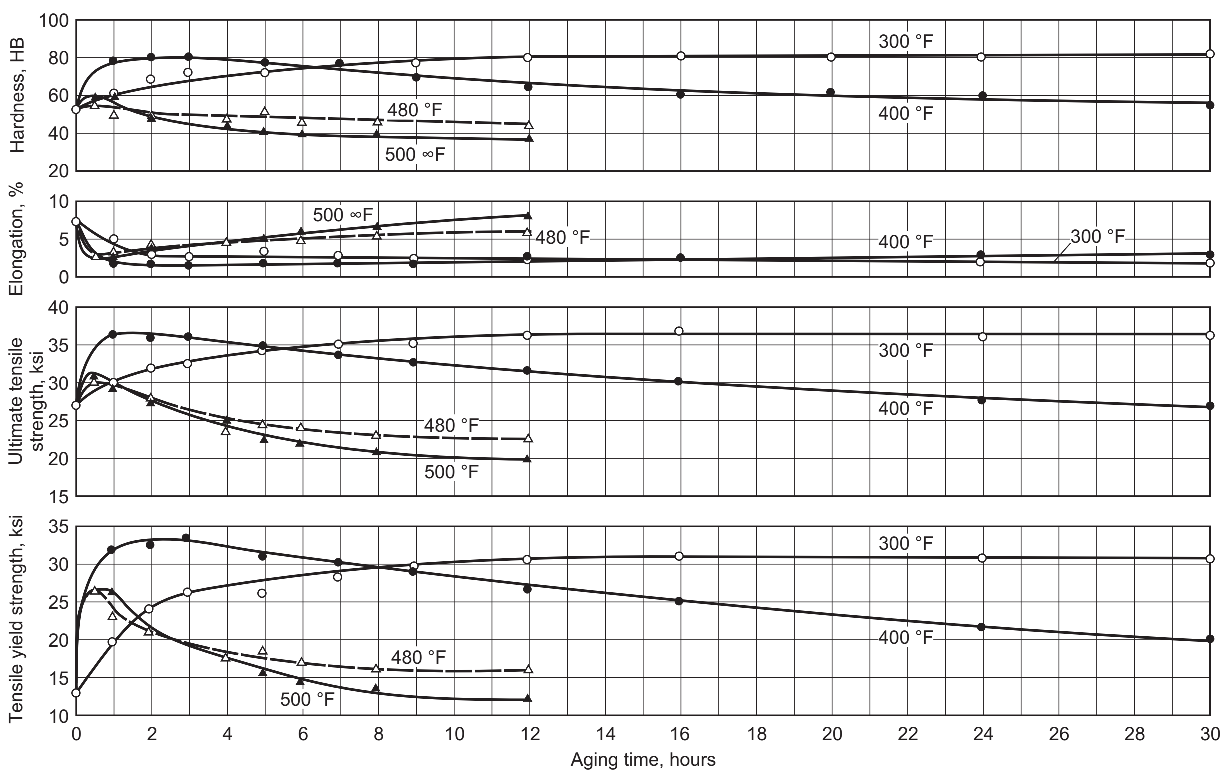

Fig. D1.94 High-temperature aging characteristics for aluminum alloy 356.0-T4, sand cast

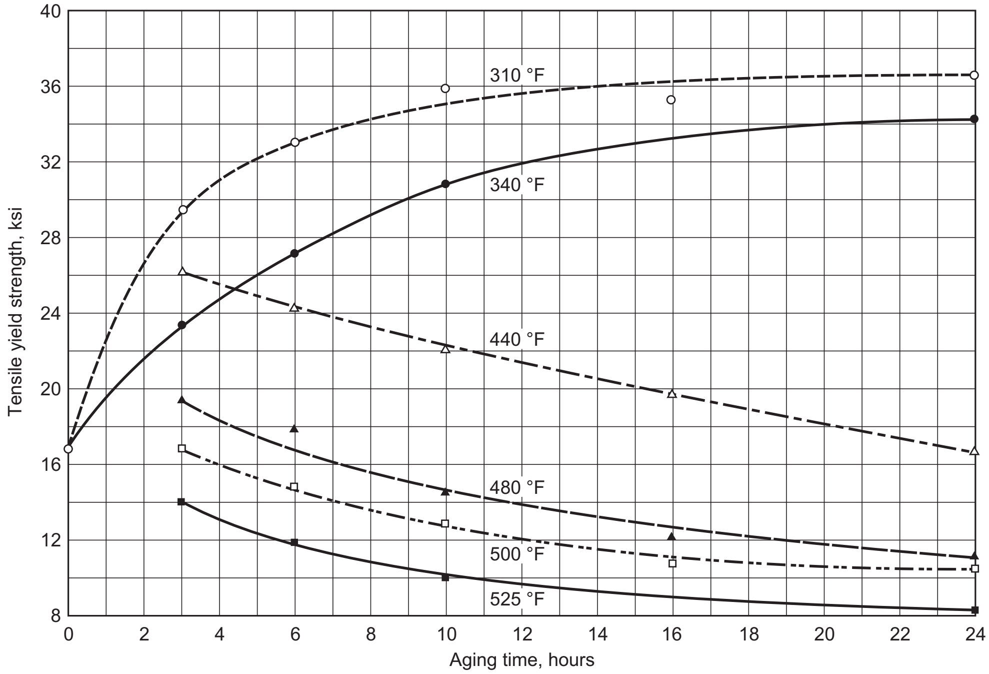

Fig. D1.95 High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 6 h at 980 °F, quenched in 110 °F water. Specimens were aged 8 months at room temperature prior to artificial aging.

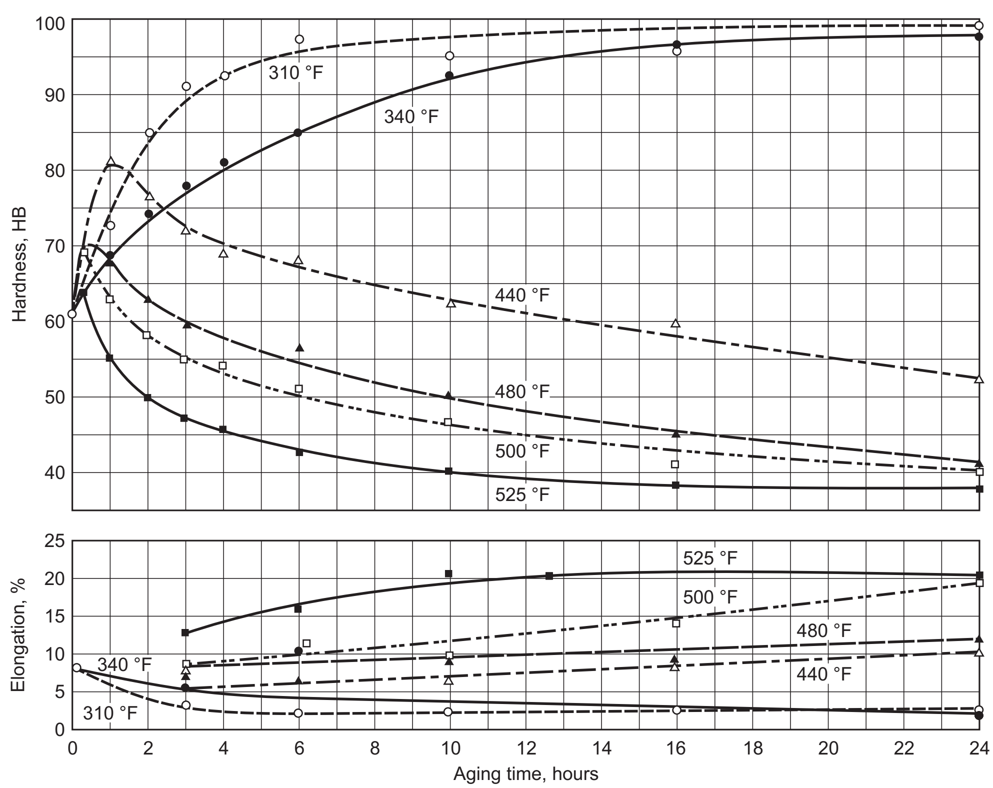

Fig. D1.96 High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 6 h at 980 °F, quenched in 110 °F water. Specimens were aged 8 months at room temperature prior to artificial aging.

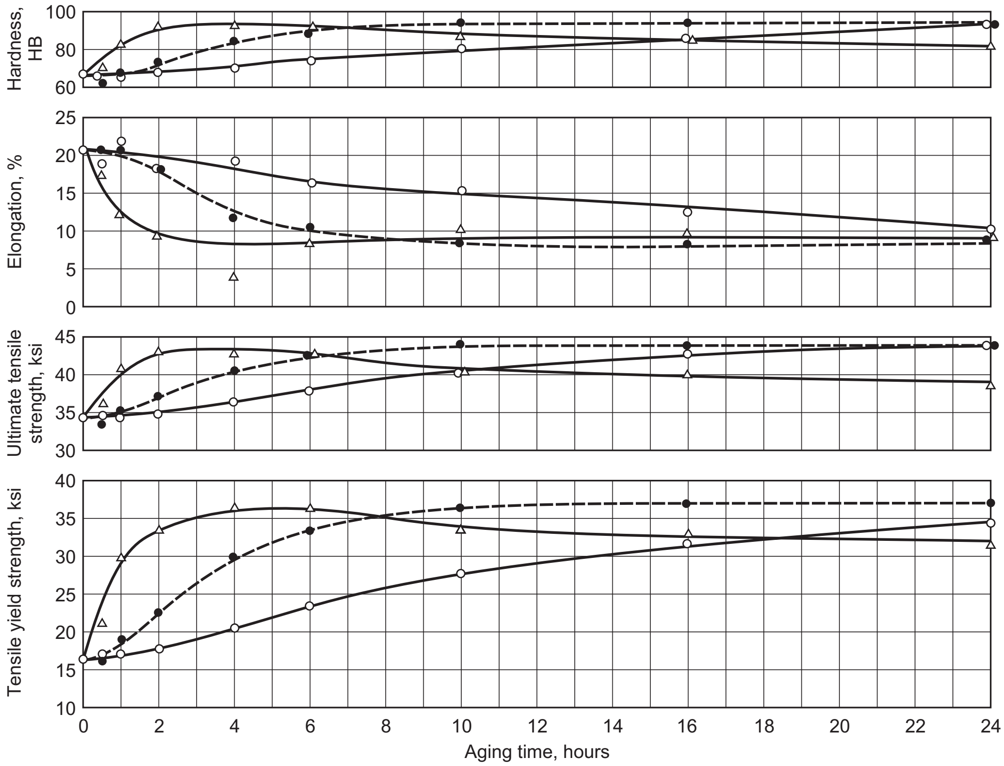

Fig. D1.97 High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 15 h at 1000 °F, quenched in boiling water. Held 24 h at room temperature

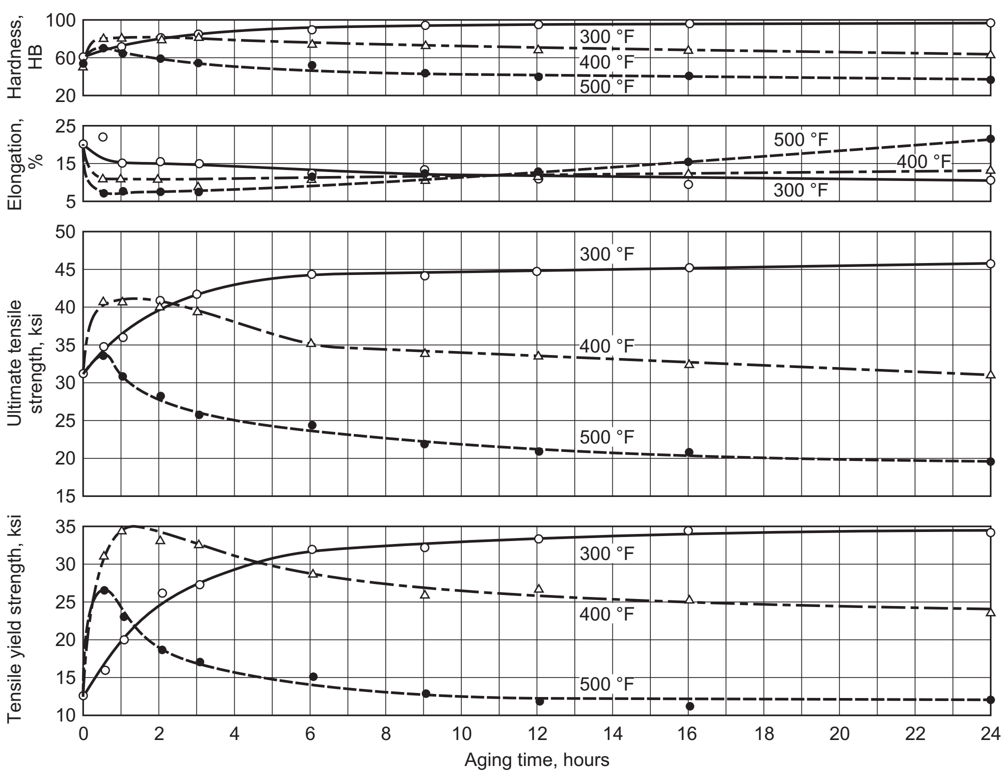

Fig. D1.98 High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold

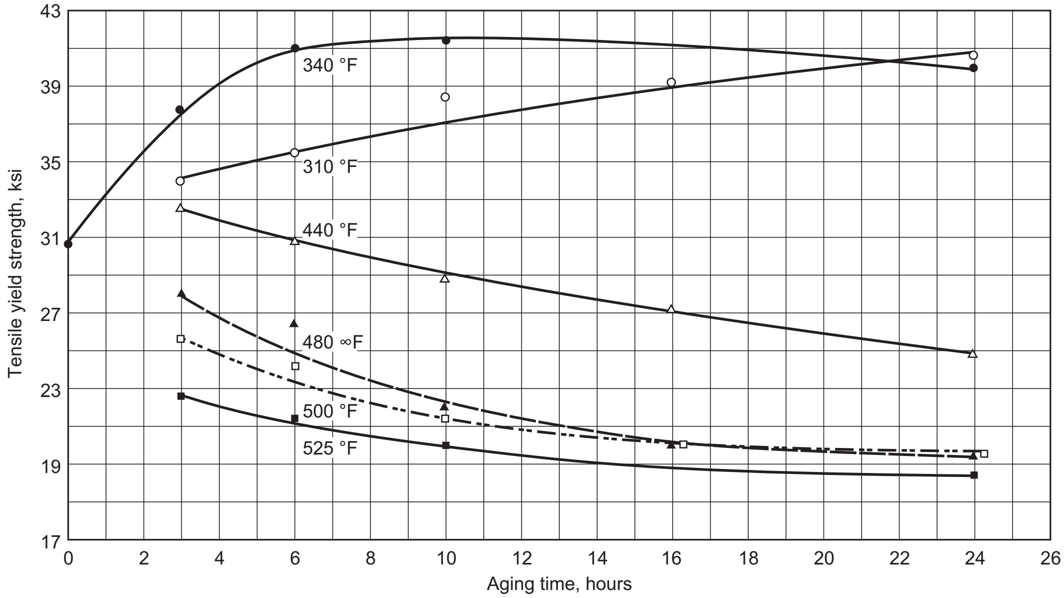

Fig. D1.99 High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 6 h at 980 °F, quenched in 110 °F water. Specimens were aged 8 months at room temperature prior to artificial aging.

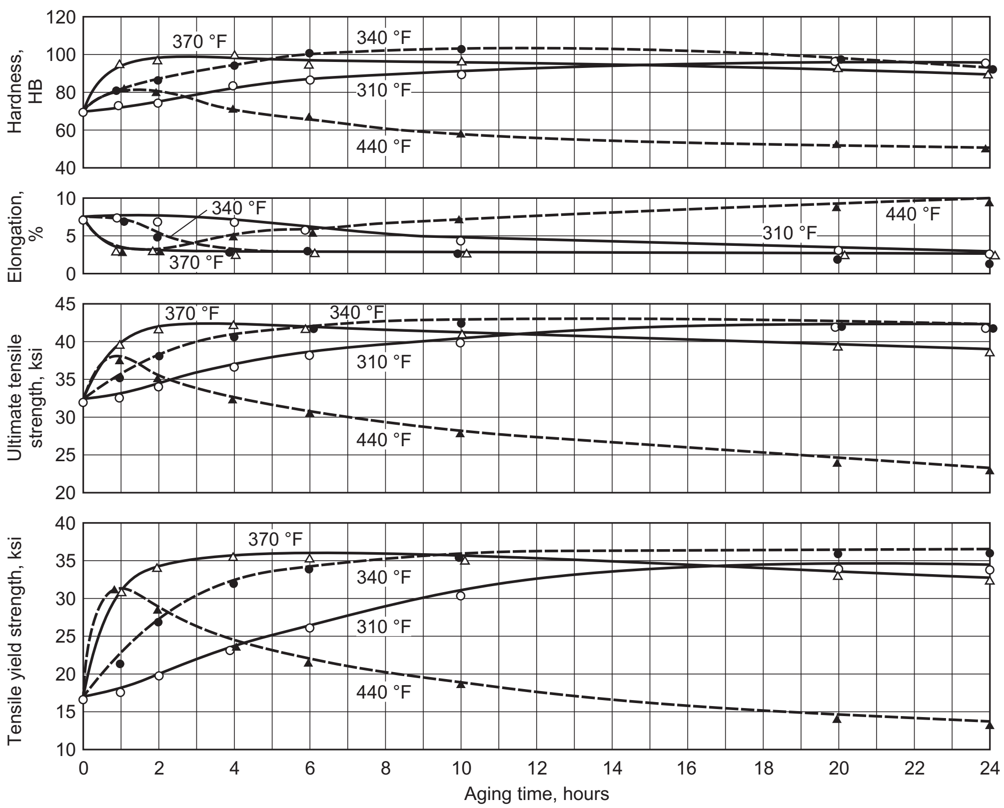

Fig. D1.100 High-temperature aging characteristics for aluminum alloy 356.0-T4, sand cast. Solution heat treated 15 h at 1000 °F, quenched in 150 °F water. Held 24 h at room temperature

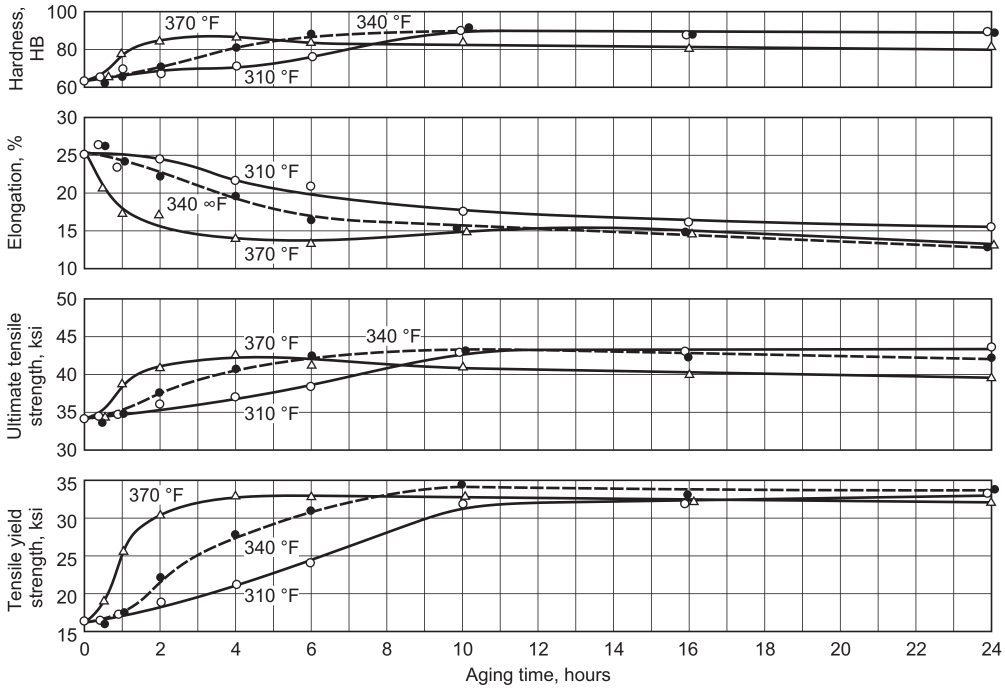

Fig. D1.101 High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 15 h at 1000 °F, quenched in 150 °F water. Held 24 h at room temperature

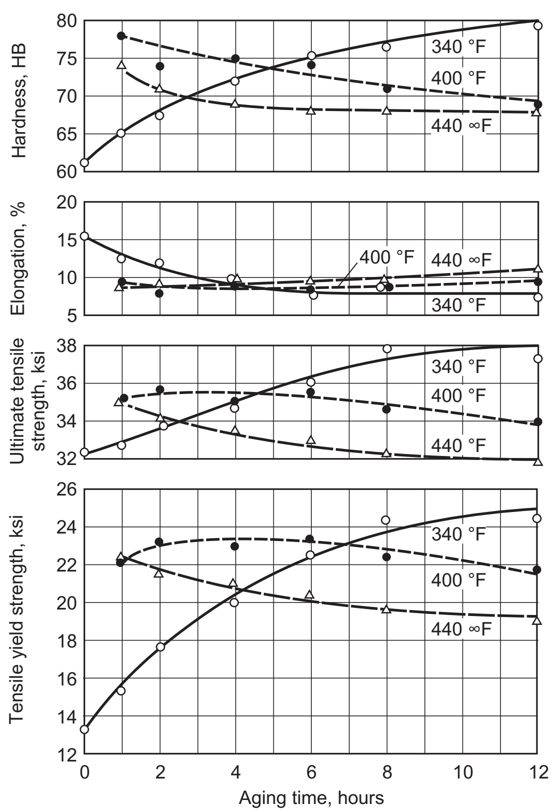

Fig. D1.102 High-temperature aging characteristics for aluminum alloy A356.0-F, permanent mold

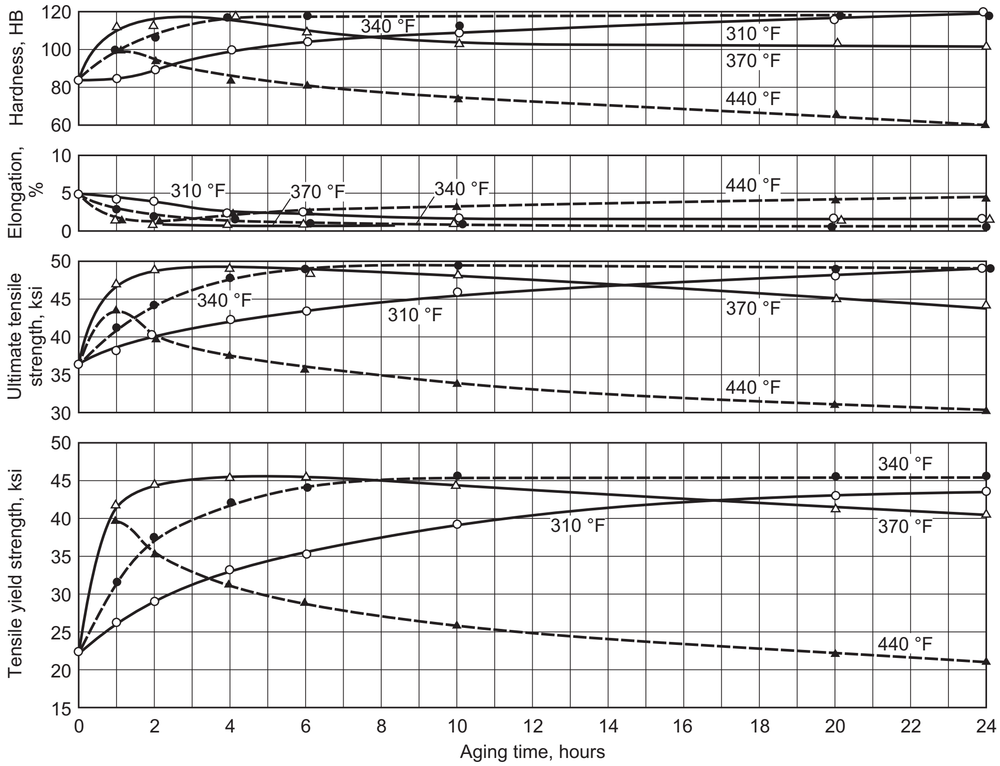

Fig. D1.103 High-temperature aging characteristics for aluminum alloy 359.0-T4, sand cast. Solution heat treated 15 h at 1000 °F, quenched in 150 °F water. Held 24 h at room temperature

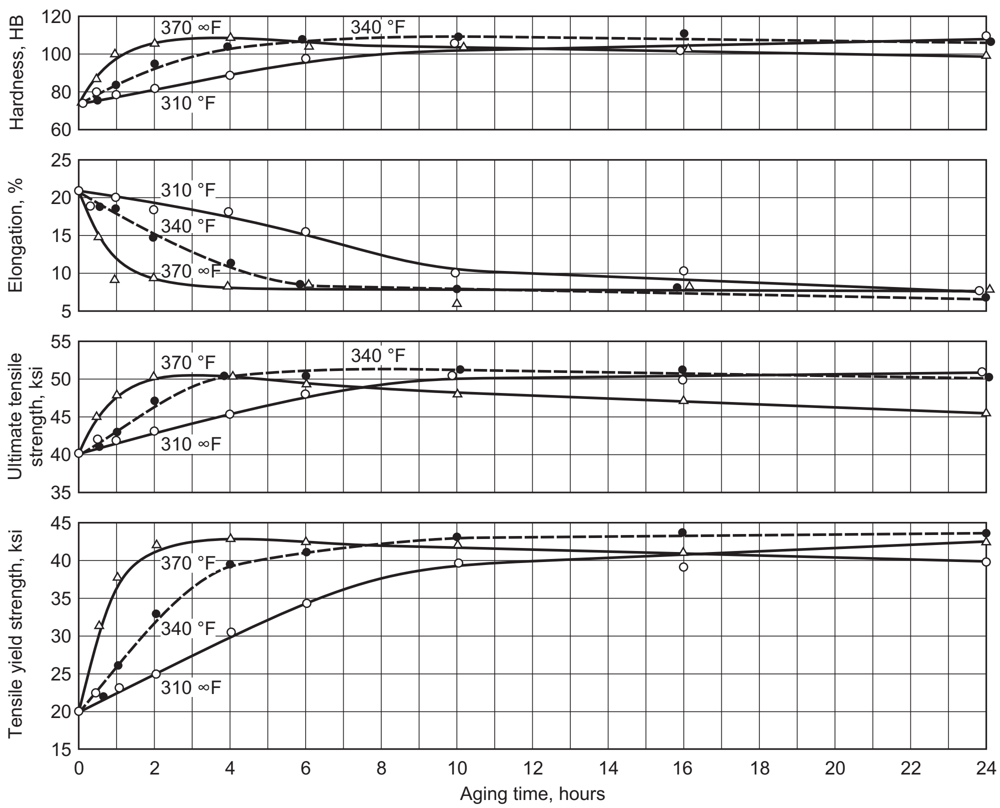

Fig. D1.104 High-temperature aging characteristics for aluminum alloy 359.0-T4, permanent mold. Solution heat treated 15 h at 1000 °F, quenched in 150 °F water. Held 24 h at room temperature

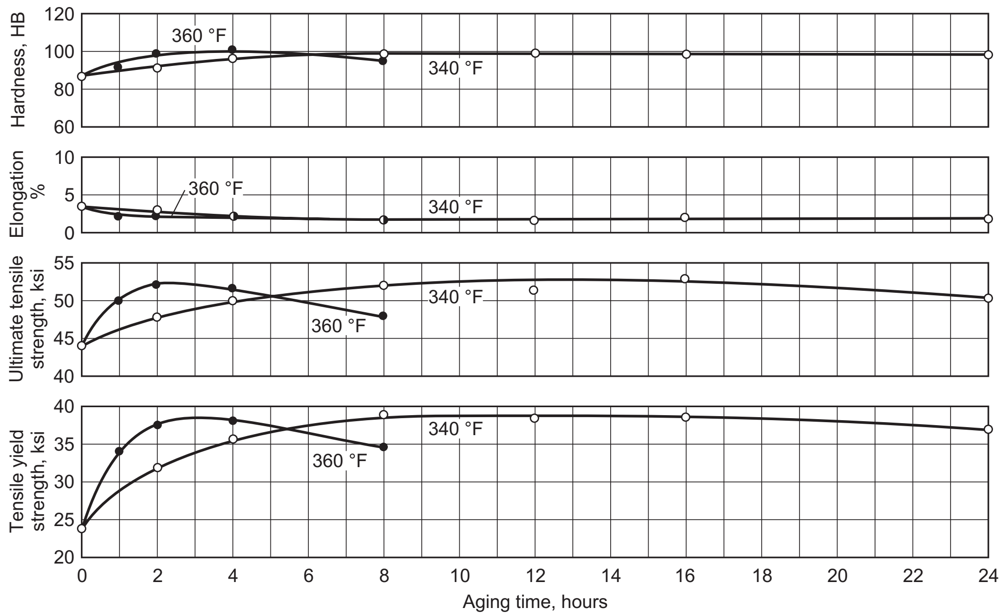

Fig. D1.105 High-temperature aging characteristics for aluminum alloy A360.0-F, die cast

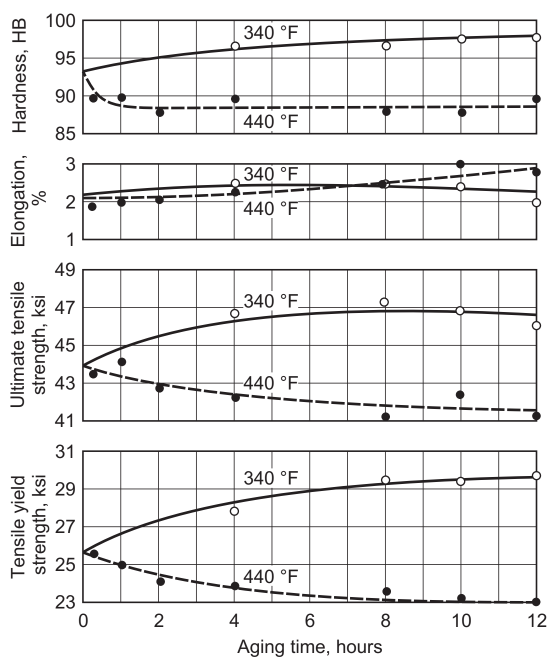

Fig. D1.106 High-temperature aging characteristics for aluminum alloy 380.0-F, die cast

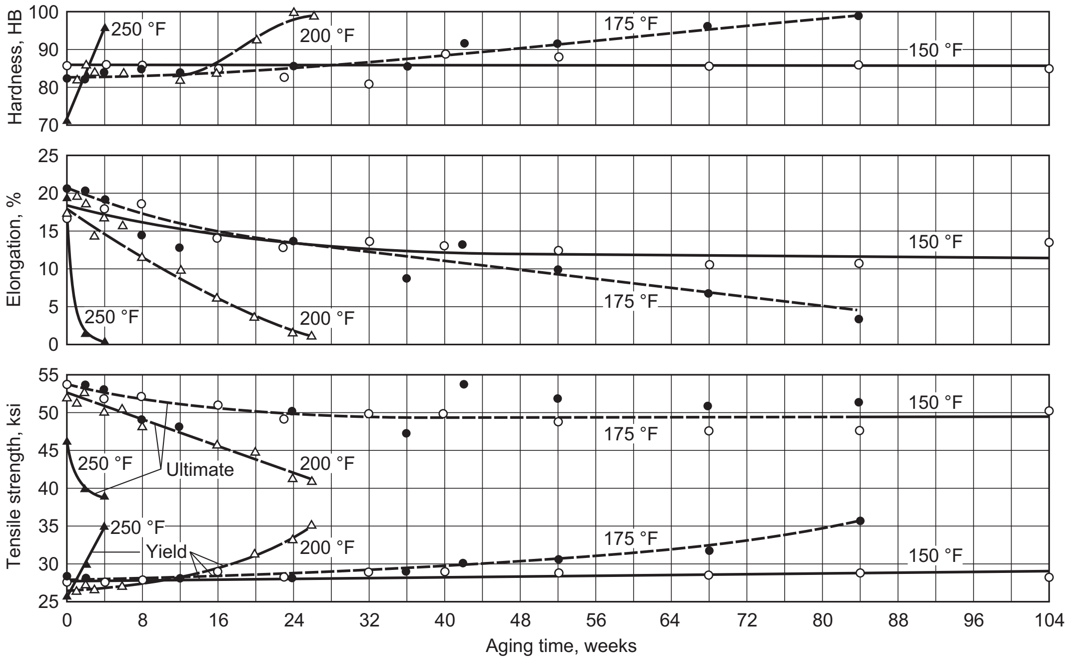

Fig. D1.107 High-temperature aging characteristics for aluminum alloy 520.0-T4. Effect of lower-temperature artificial aging. Tested at room temperature

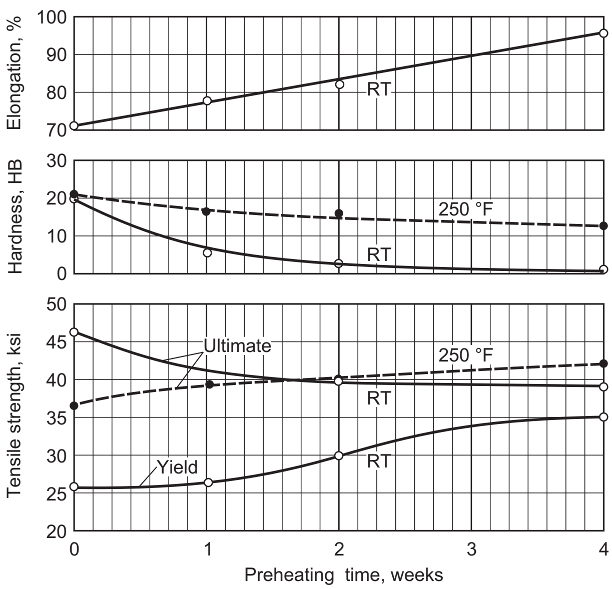

Fig. D1.108 High-temperature aging characteristics for aluminum alloy 520.0-T4, sand cast. Effect of preheating at 250 °F. Tested at room temperature

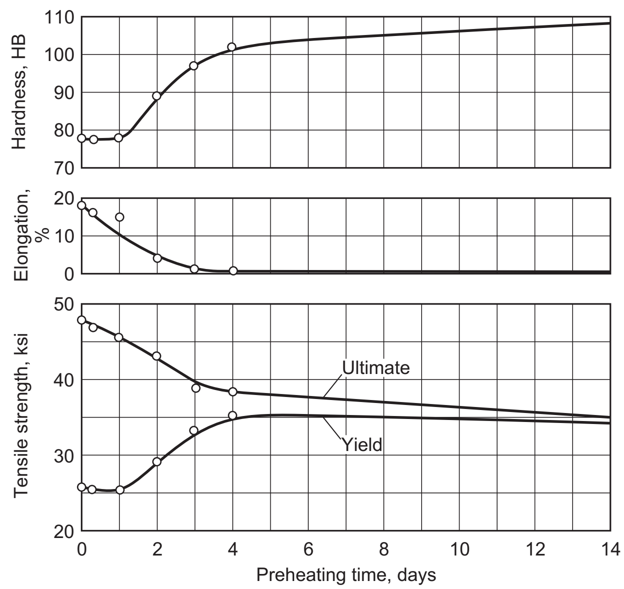

Fig. D1.109 High-temperature aging characteristics for aluminum alloy 520.0-T4, sand cast. Effect of aging at 300 °F. Tested at room temperature

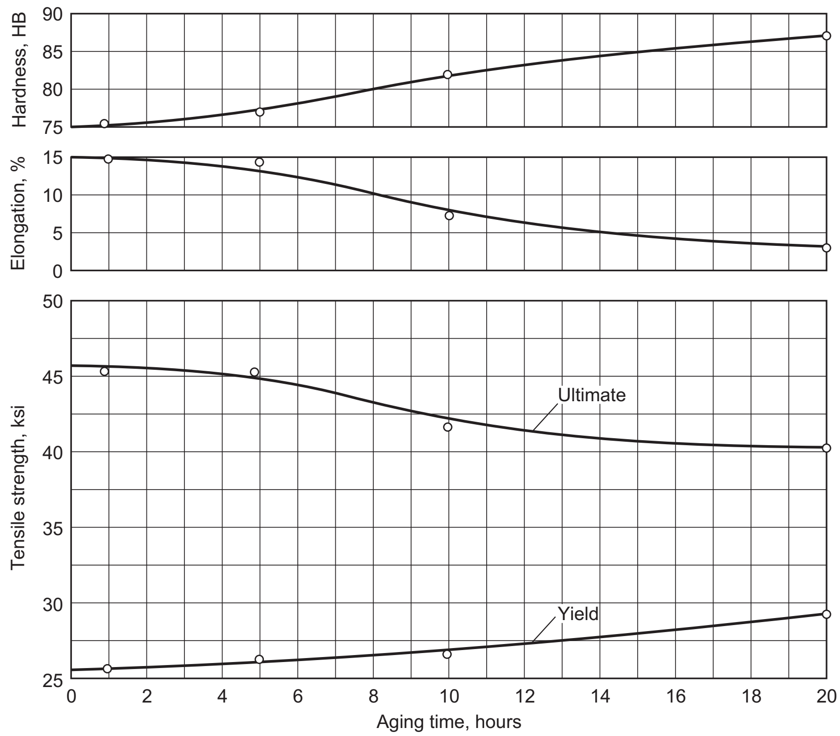

Fig. D1.110 High-temperature aging characteristics for aluminum alloy 520.0-T4, sand cast. Effect of aging at 325 °F. Tested at room temperature

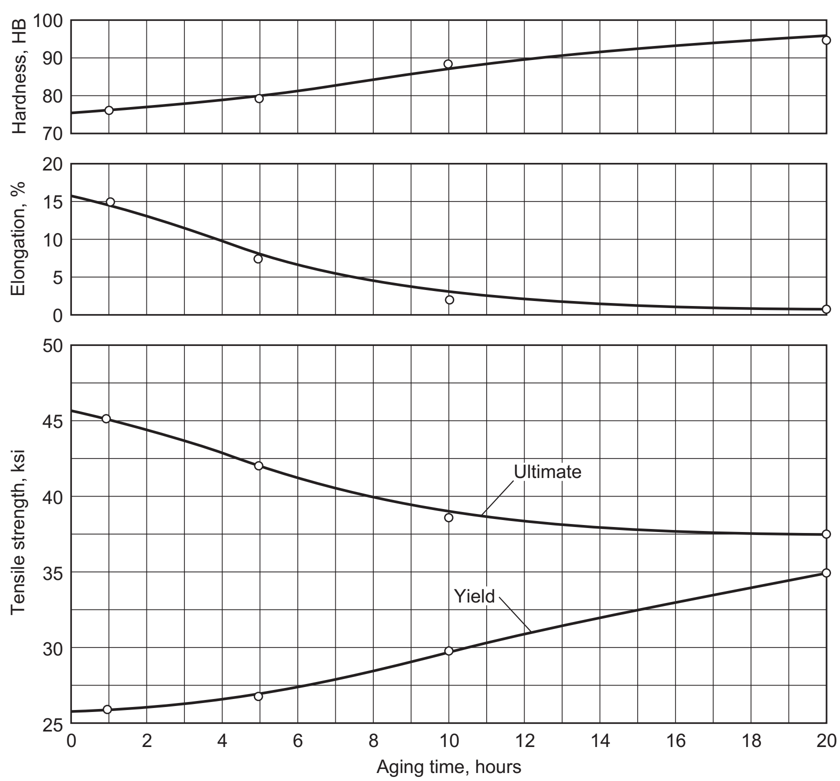

Fig. D1.111 High-temperature aging characteristics for aluminum alloy 520.0-T4, sand cast. Effect of aging at 350 °F. Tested at room temperature

Aluminum Alloy Castings: Properties, Processes, and Applications
J.G. Kaufman, E.L. Rooy, p 175-192
DOI:10.1361/aacp2004p175

DATA SET 2

Growth Curves

This data set contains approximately 50 growth curves for a wide range of aluminum casting alloys, providing experimental evidence of permanent dimensional change with time at various temperatures. All of these curves were developed at Alcoa Laboratories Cleveland Casting Research Division.

The purpose in making such measurements is to determine the dimensional changes that must be anticipated during service in applications where close dimensional tolerances are required.

Hardness values shown were the product of corresponding aging response studies in which measurements were made on individual lots considered representative of the respective alloys and tempers. They have not been normalized to any typical or average compositions for the individual alloys and tempers.

The growth factor is given in units of 10^{-4} in./in.; the values on the axis are to be multiplied by 10^{-4}. This representation is standard industry practice. The growth factor is unitless, so the value is identical in the SI system.

Brinell hardness (HB) was recorded in many of these tests. Hardness testing employed a 4.9 kN (500 kgf) load with a 10 mm ball, in accordance with ASTM E 10.

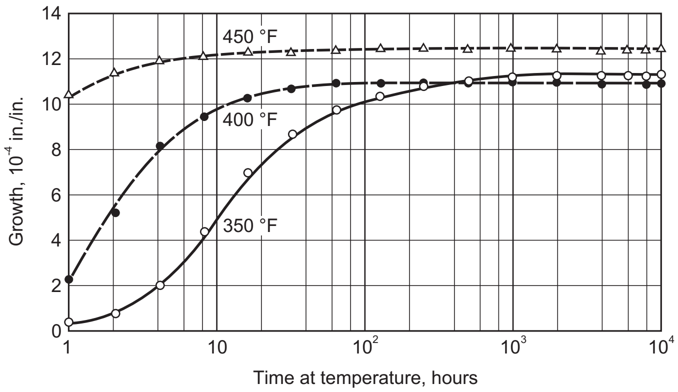

Fig. D2.1 Growth curves for aluminum alloy 238.0-F, permanent mold. Test specimen: 1.125 diam × 12 in. rod

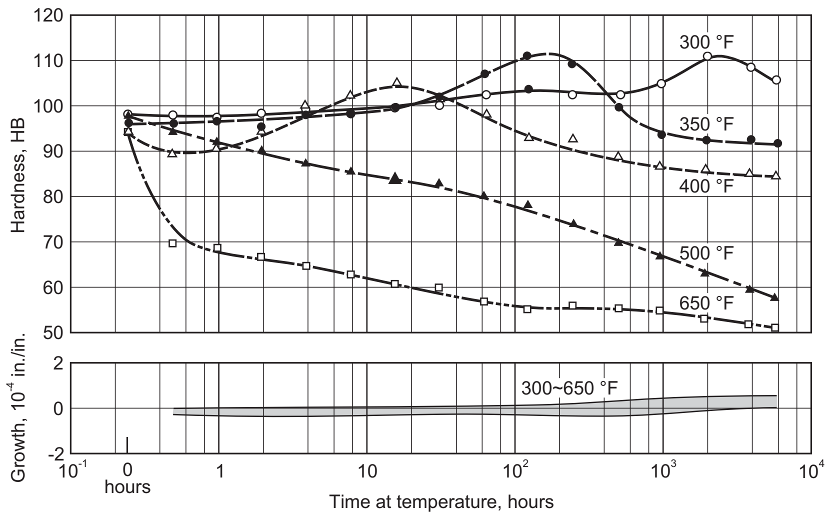

Fig. D2.2 Growth and hardness curves for aluminum alloy 242.0-F, permanent mold. Test specimen 1.125 diam × 12 in. rod

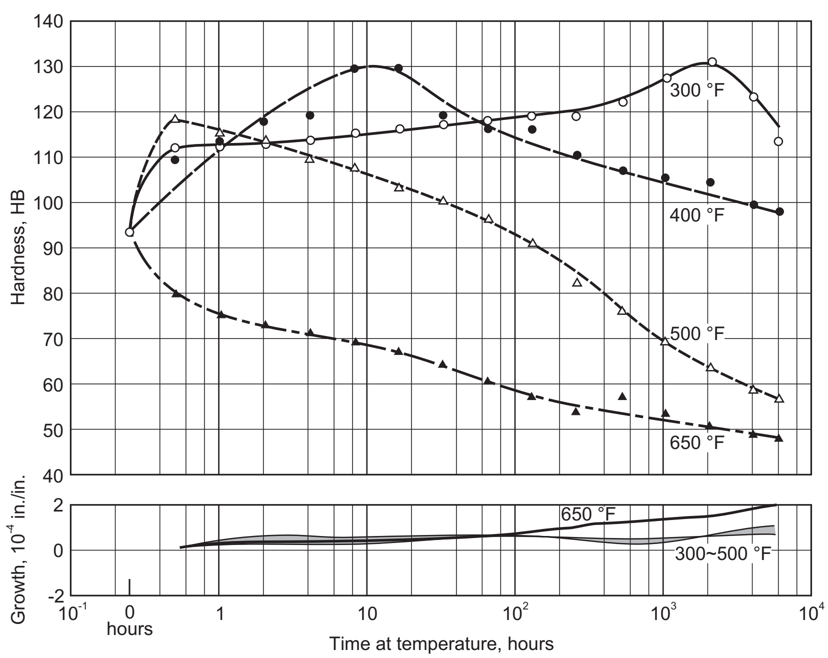

Fig. D2.3 Growth and hardness curves for aluminum alloy 242.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

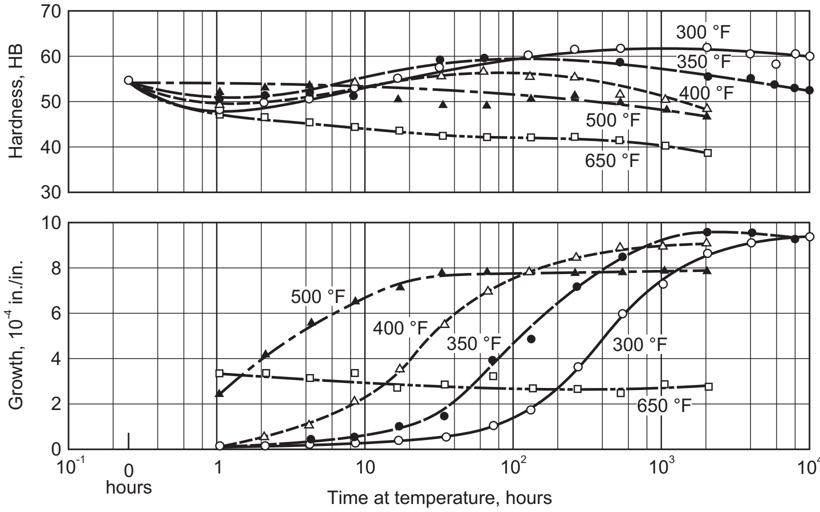

Fig. D2.4 Growth and hardness curves for aluminum alloy 295.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

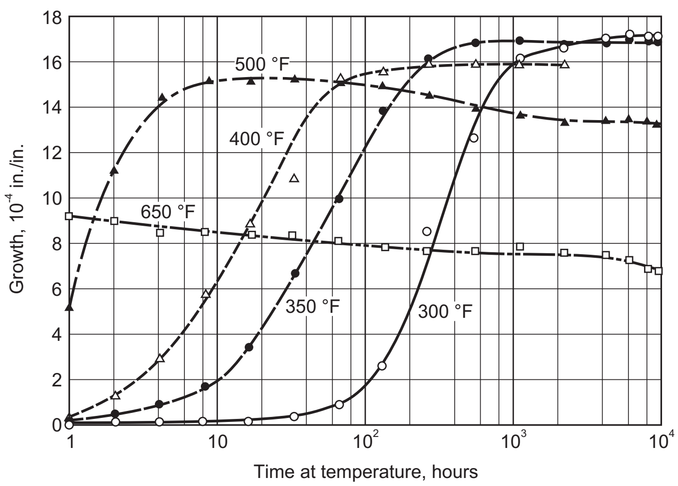

Fig. D2.5 Growth curves for aluminum alloy 295.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

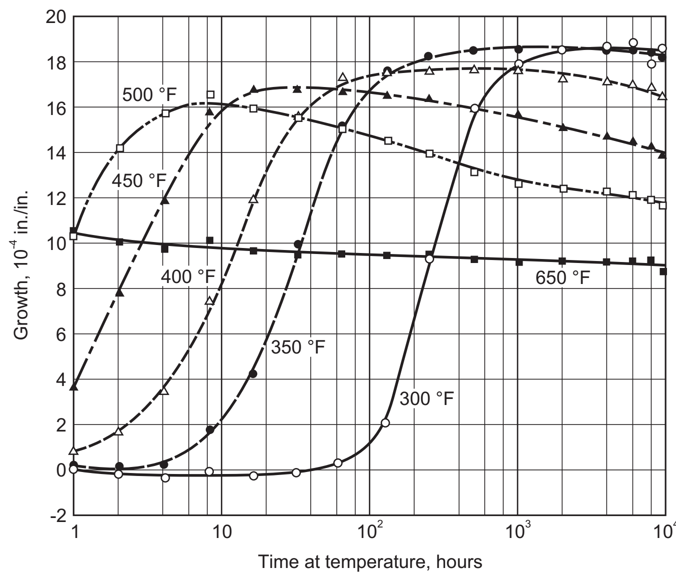

Fig. D2.6 Growth curves for aluminum alloy B295.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 950 °F, boiling water quench

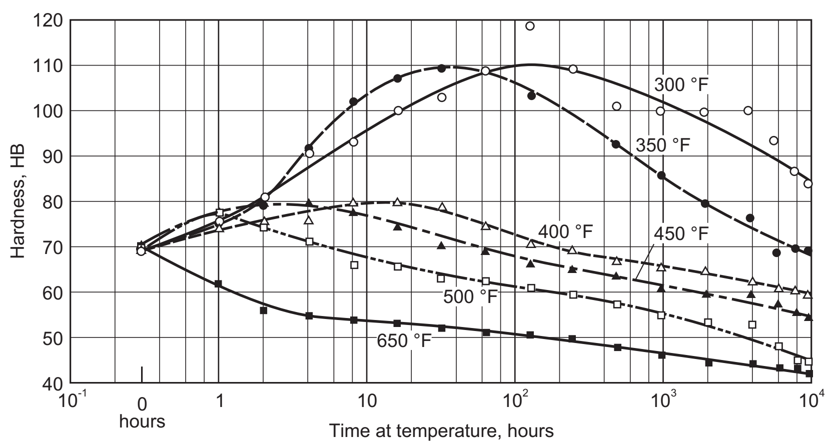

Fig. D2.7 Hardness curves for aluminum alloy B295.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 940 °F, boiling water quench

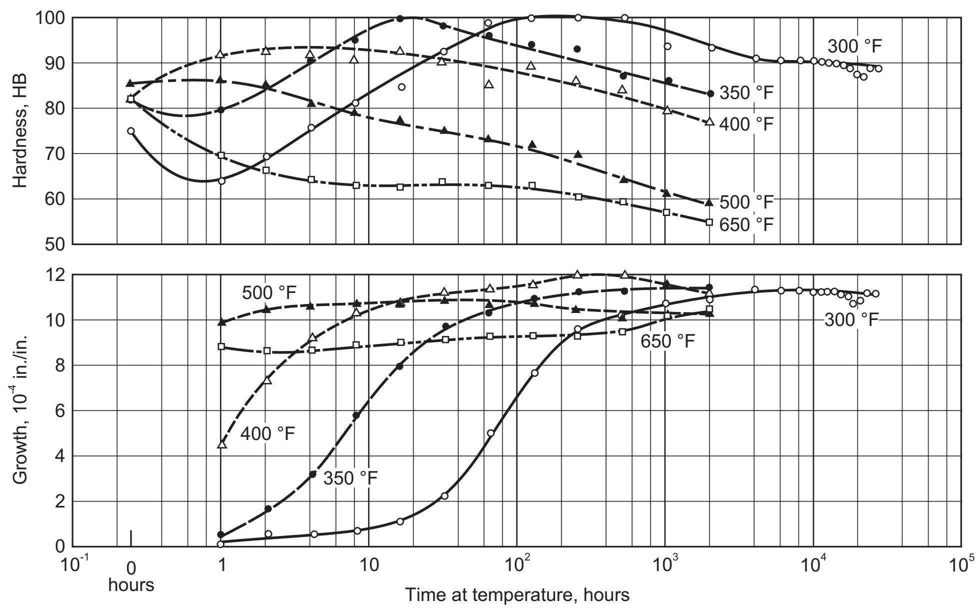

Fig. D2.8 Growth and hardness curves for aluminum alloy 319.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

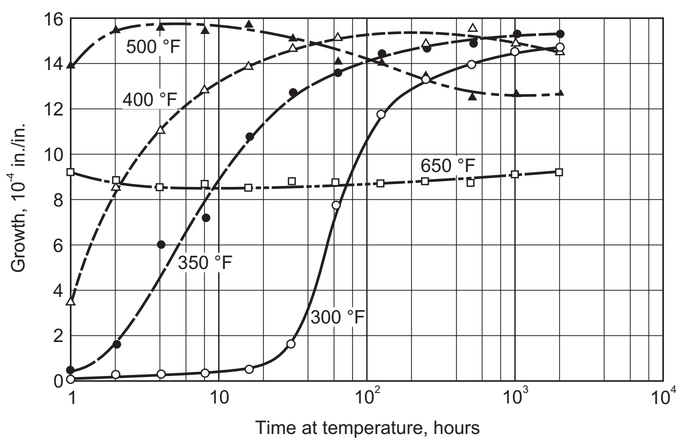

Fig. D2.9 Growth curves for aluminum alloy 319.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

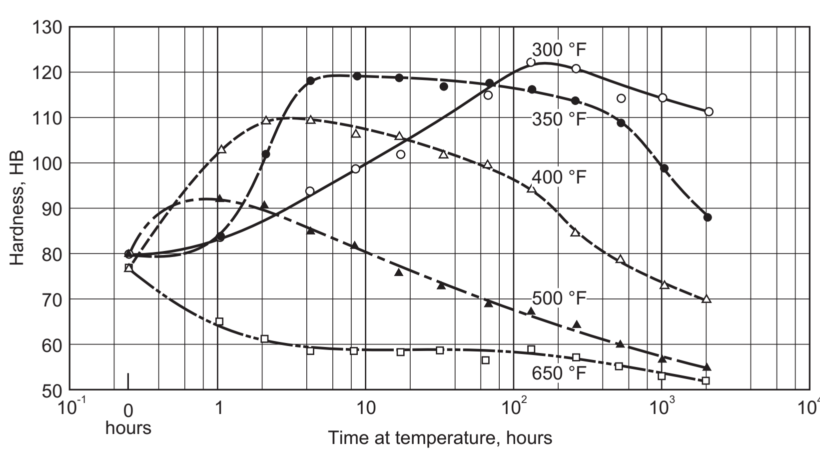

Fig. D2.10 Hardness curves for aluminum alloy 319.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

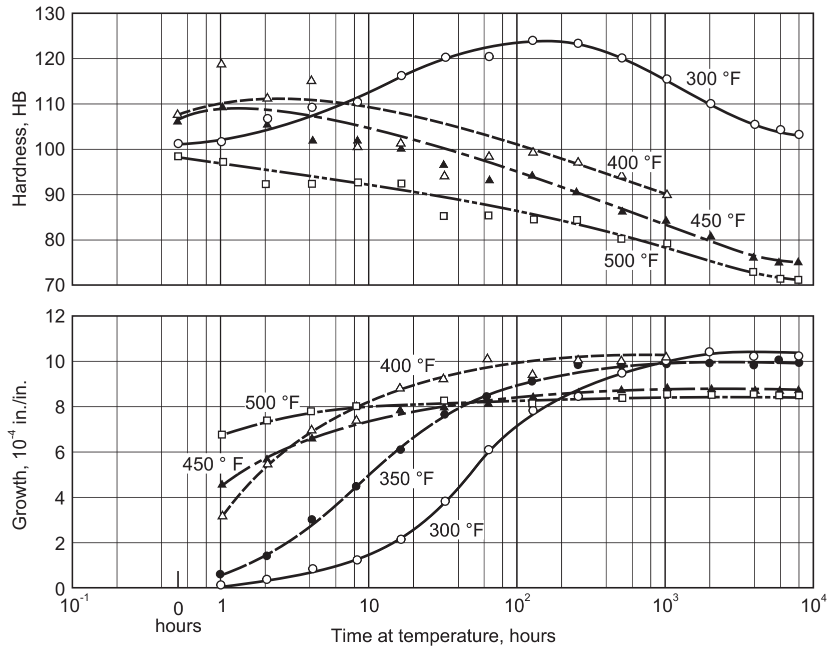

Fig. D2.11 Growth and hardness curves for aluminum alloy 332.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

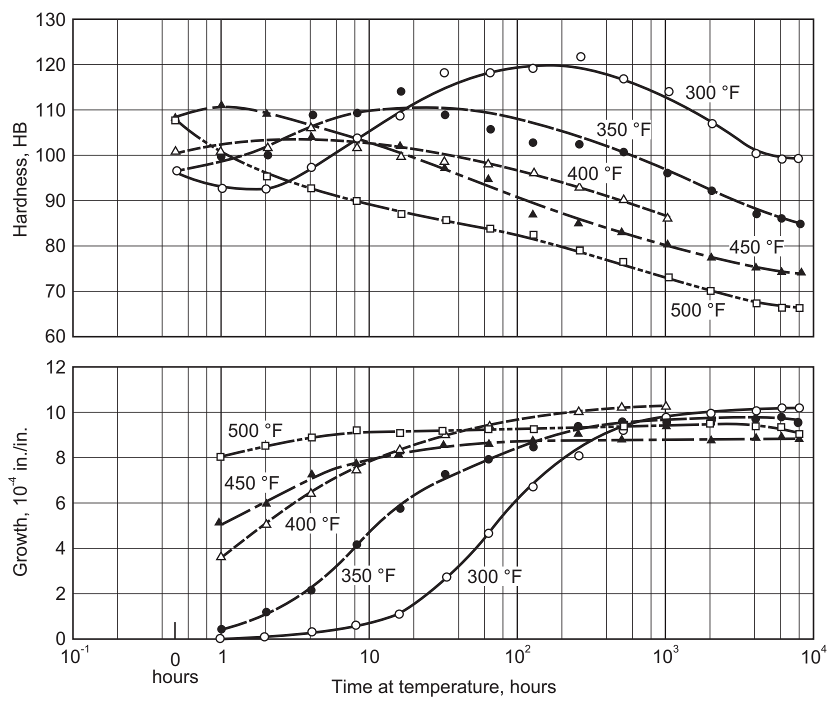

Fig. D2.12 Growth and hardness curves for aluminum alloy 333.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

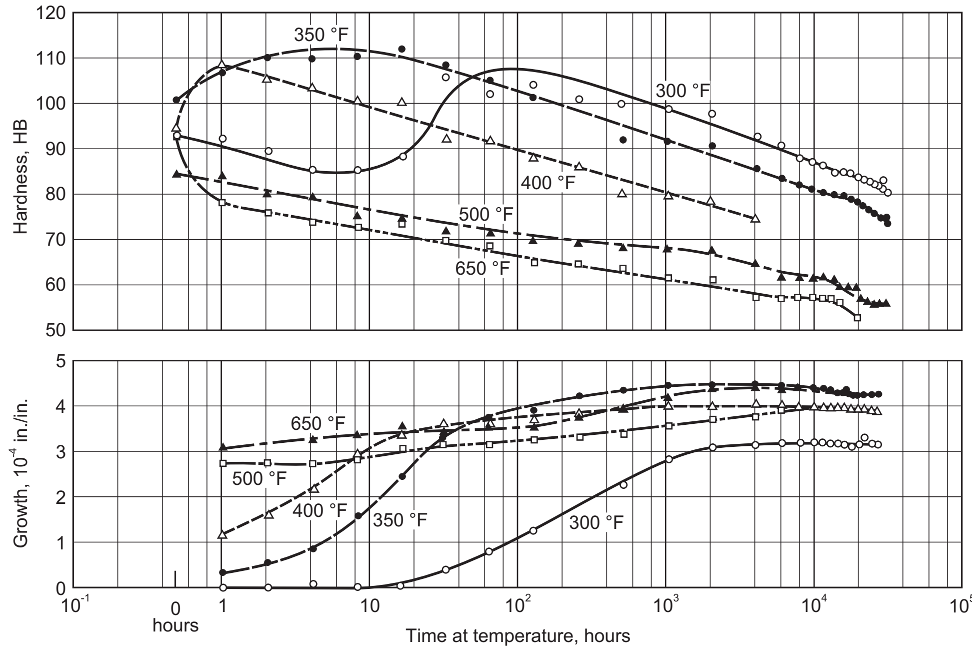

Fig. D2.13 Growth and hardness curves for aluminum alloy 336.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

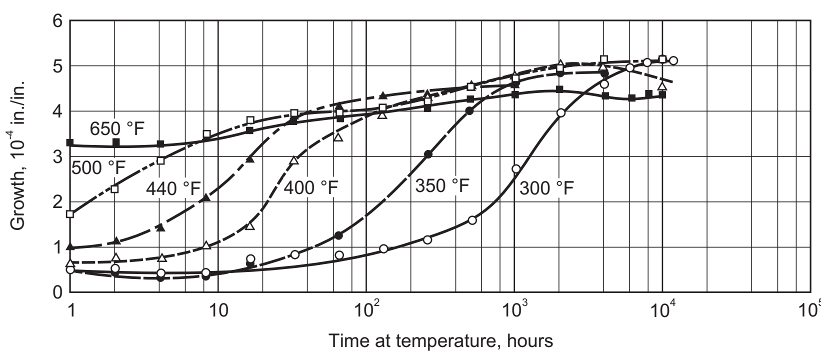

Fig. D2.14 Growth curves for aluminum alloy 336.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 950 °F, boiling water quench

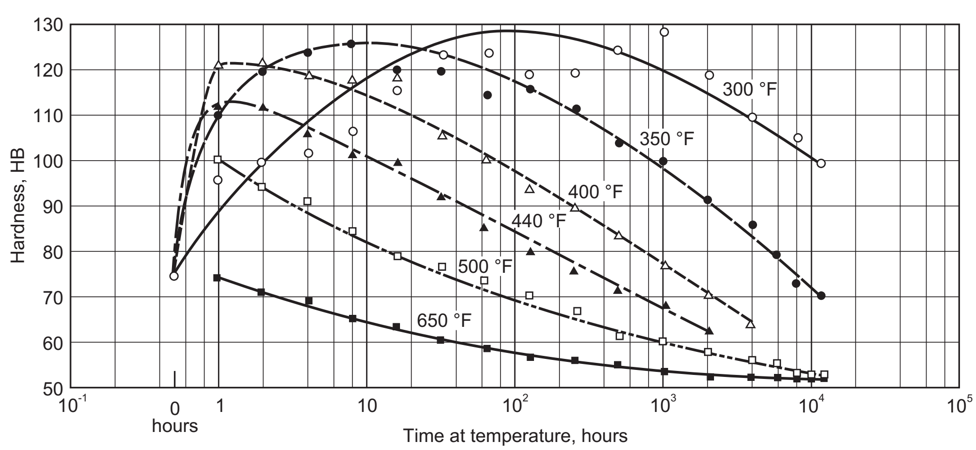

Fig. D2.15 Hardness curves for aluminum alloy 336.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 950 °F, boiling water quench

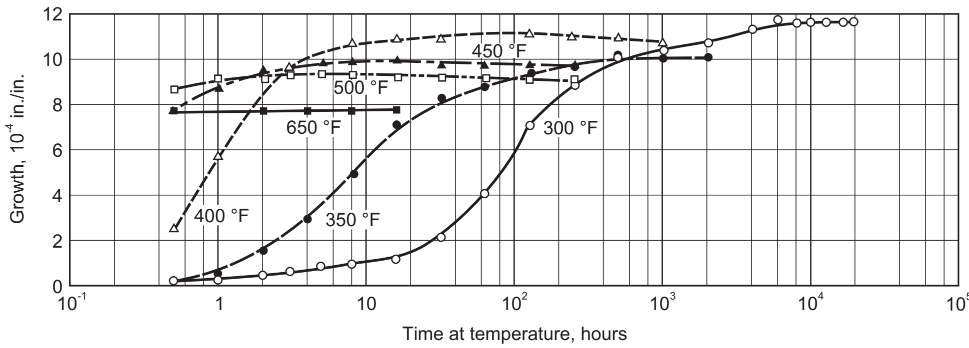

Fig. D2.16 Growth curves for aluminum alloy 355.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

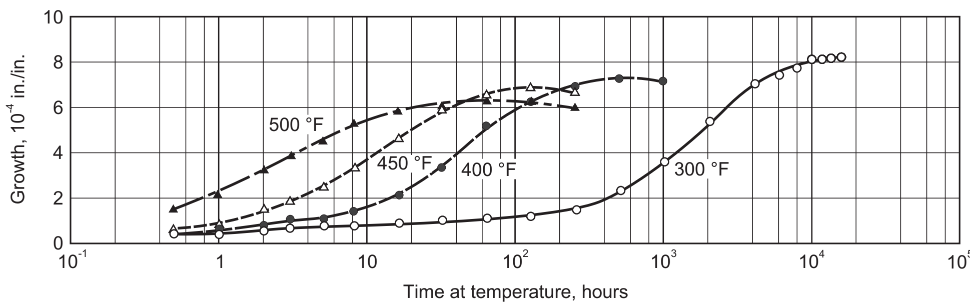

Fig. D2.17 Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 940 °F, boiling water quench

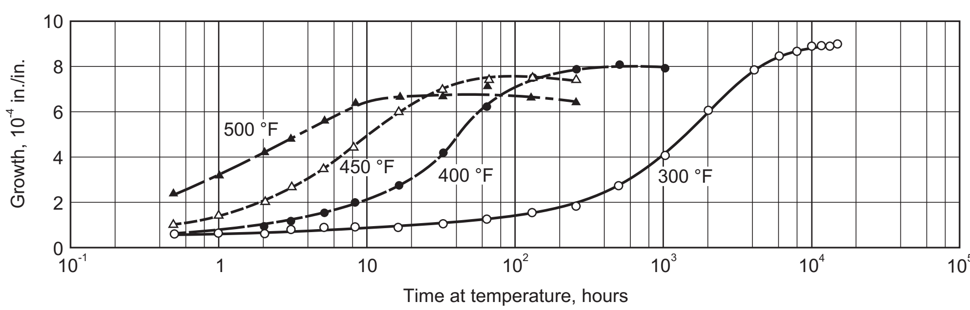

Fig. D2.18 Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

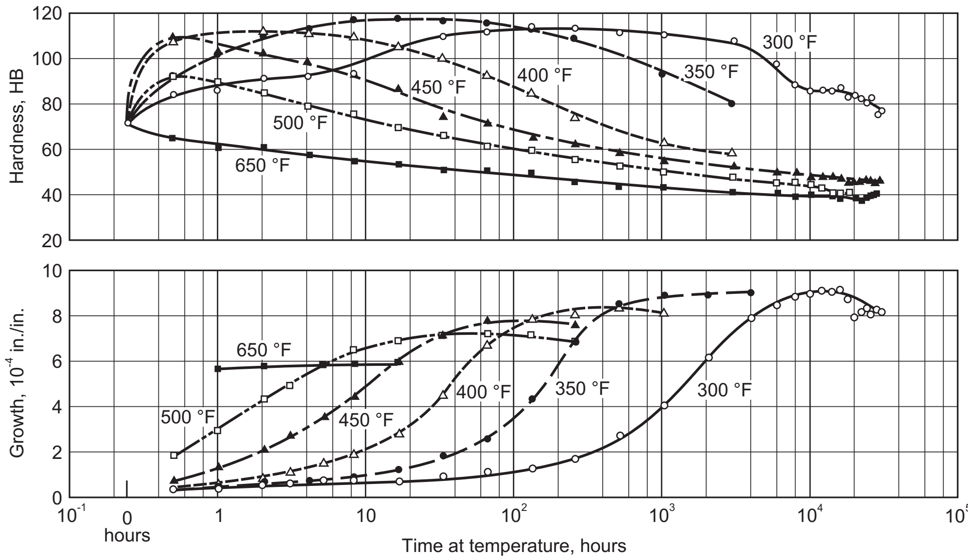

Fig. D2.19 Growth and hardness curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 980 °F, boiling water quench

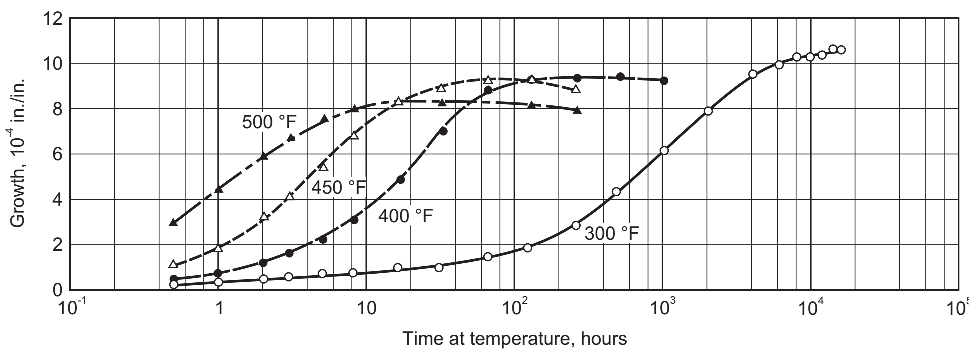

Fig. D2.20 Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 1000 °F, boiling water quench

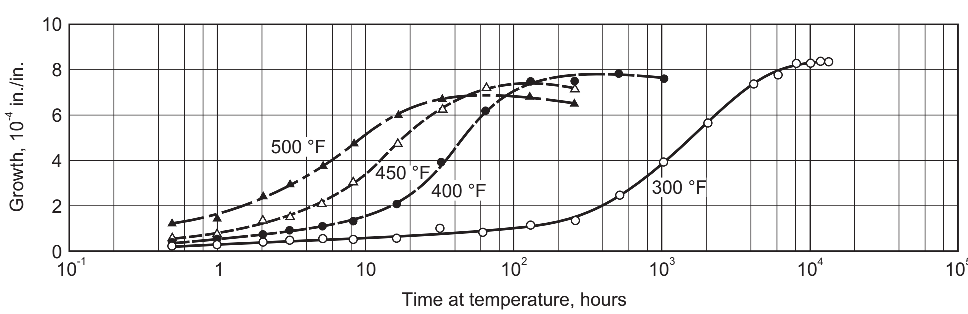

Fig. D2.21 Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 940 °F, cold water quench

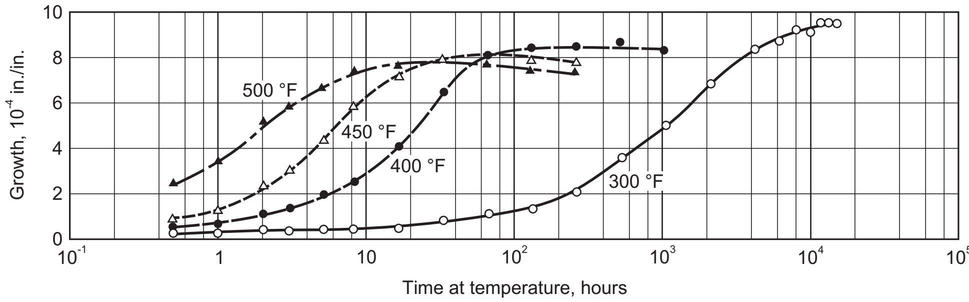

Fig. D2.22 Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 960 °F, cold water quench

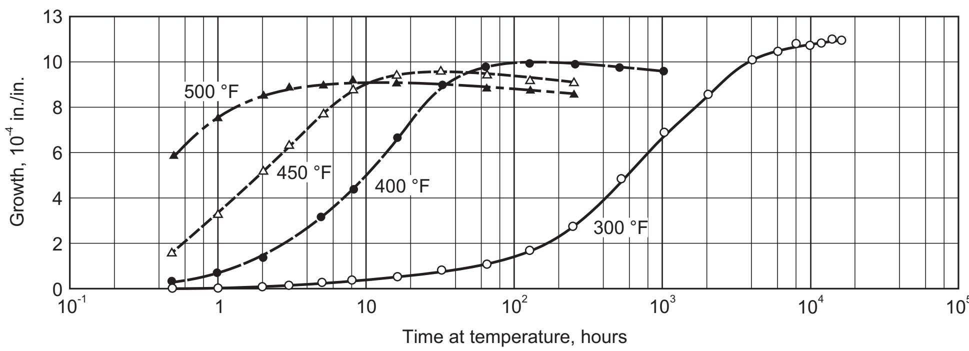

Fig. D2.23 Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 1000 °F, cold water quench

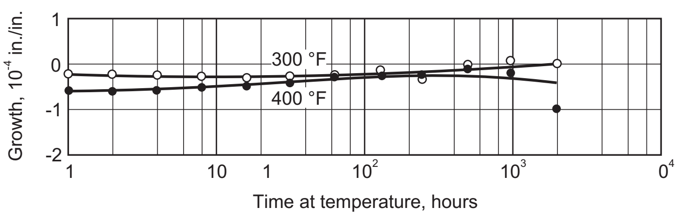

Fig. D2.24 Growth curves for aluminum alloy 355.0-T51, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 8 h at 440 °F

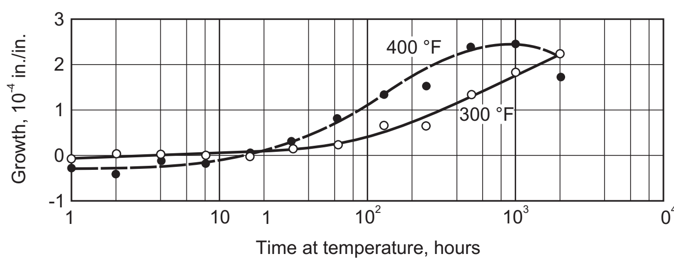

Fig. D2.25 Growth curves for aluminum alloy 355.0-T7, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 5 h at 700 °F plus 12 h at 850 °F, boiling water quench, 8 h at 440 °F

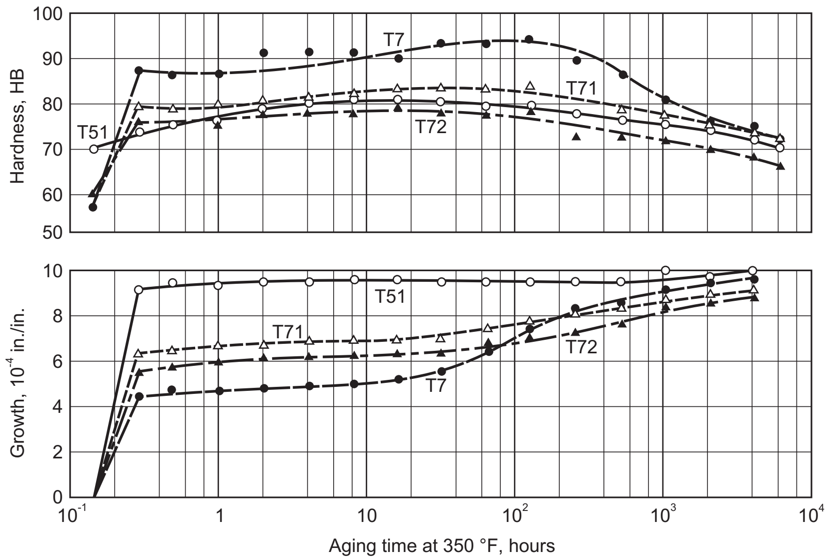

Fig. D2.26 Growth and hardness curves for aluminum alloy 355.0 with various commercial tempers and aging at 350 °F, permanent mold. Zero hour data is as-cast. Data at 0.3 h is after the commercial heat treatment. Data for aging at 350 °F is then given. Specimen: 1.125 diam × 12 in. rod. Treatment: T51, 8 h at 440 °F; T7, 980 °F, boiling water quench, 5 h at 540 °F; T71, 980 °F, boiling water quench, 5 h at 480 °F; T72, 980 °F boiling water quench, 5 h at 500 °F

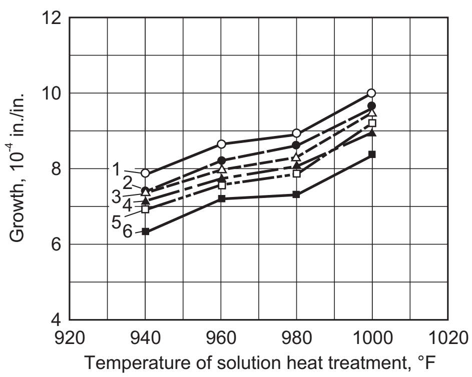

Fig. D2.27 Maximum growth of aluminum alloy 355.0-T4 under various conditions of solution heat treatment and quench: Curve 1, cold water quench, aging at 400 °F. Curve 2, cold water quench, aging at 450 °F. Curve 3, boiling water quench, aging at 400 °F. Curve 4, cold water quench, aging at 500 °F. Curve 5, boiling water quench, aging at 450 °F. Curve 6, boiling water quench, aging at 500 ° F. Permanent mold. Specimen: 1.125 diam × 12 in. rod

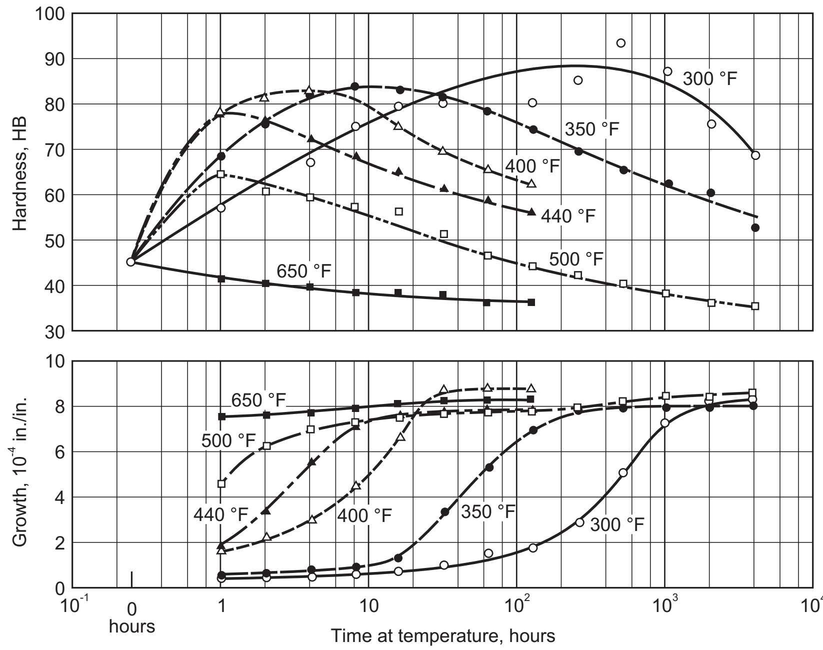

Fig. D2.28 Growth and hardness curves for aluminum alloy 356.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 980 °F, boiling water quench

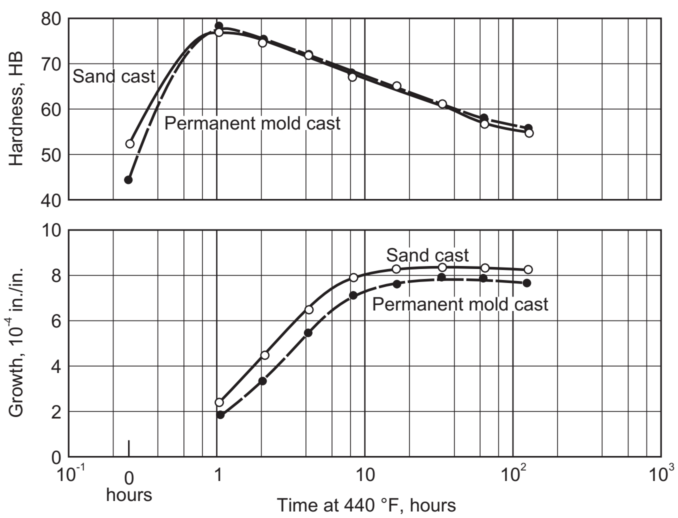

Fig. D2.29 Growth and hardness curves for aluminum alloy 356.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 980 °F, boiling water quench. Comparison of sand cast and permanent mold

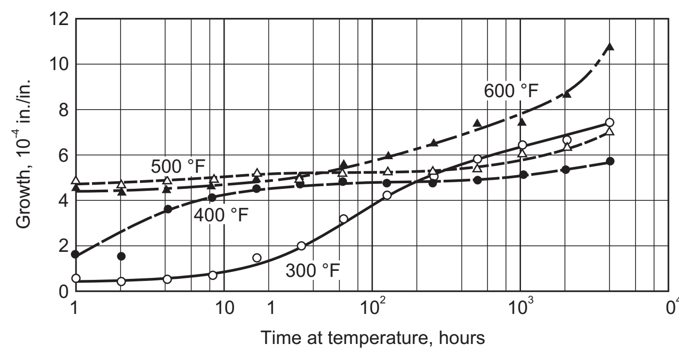

Fig. D2.30 Growth curves for aluminum alloy 360.0-F, die cast. Specimen: 3/16 in. thick plate

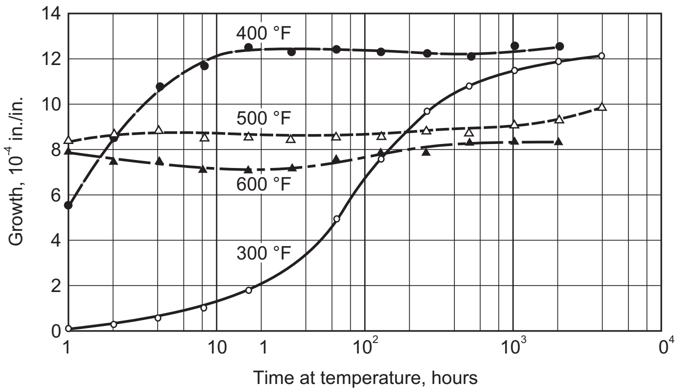

Fig. D2.31 Growth curves for aluminum alloy 380.0-F, die cast. Specimen: 3/16 in. thick plate

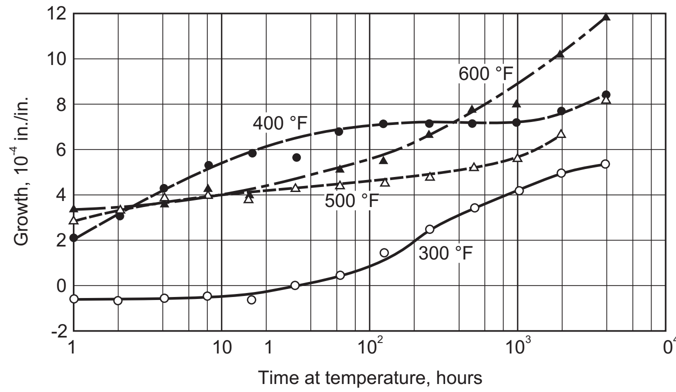

Fig. D2.32 Growth curves for aluminum alloy 384.0-F, die cast. Specimen: 5/16 in. thick plate

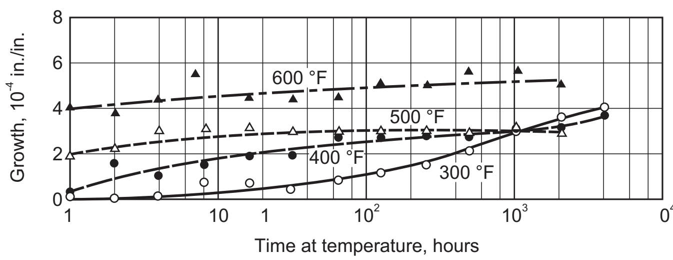

Fig. D2.33 Growth curves for aluminum alloy 413.0-F, die cast. Specimen: 3/16 in. thick plate

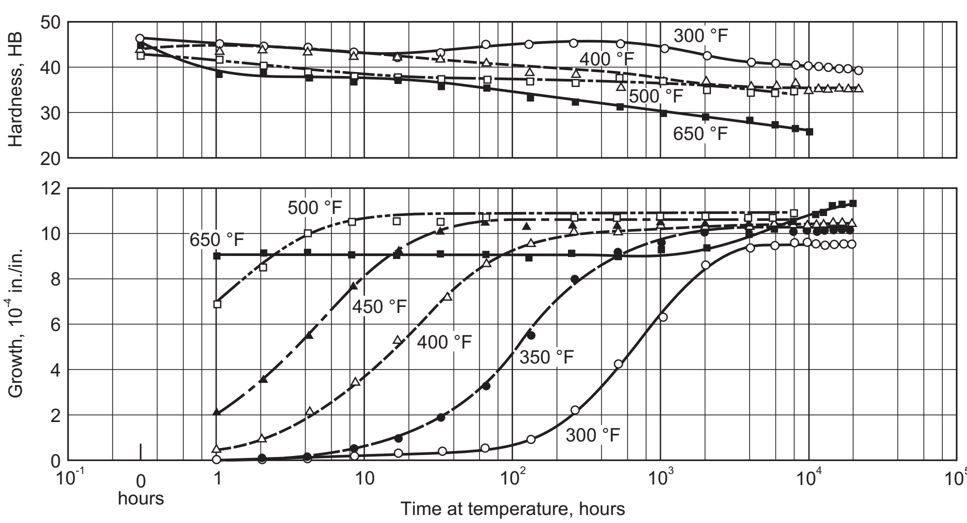

Fig. D2.34 Growth and hardness curves for aluminum alloy 443.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

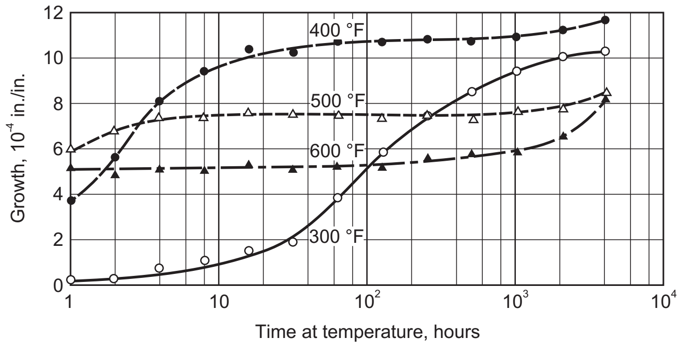

Fig. D2.35 Growth curves for aluminum alloy 443.0-F, die cast. Specimen: 3/16 in. thick plate

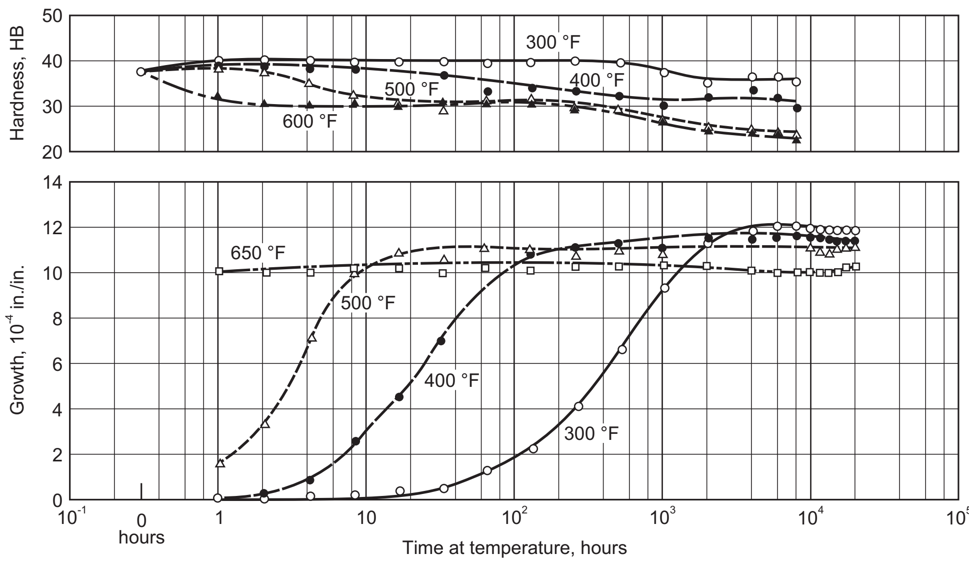

Fig. D2.36 Growth and hardness curves for aluminum alloy 443.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 1000 °F, boiling water quench

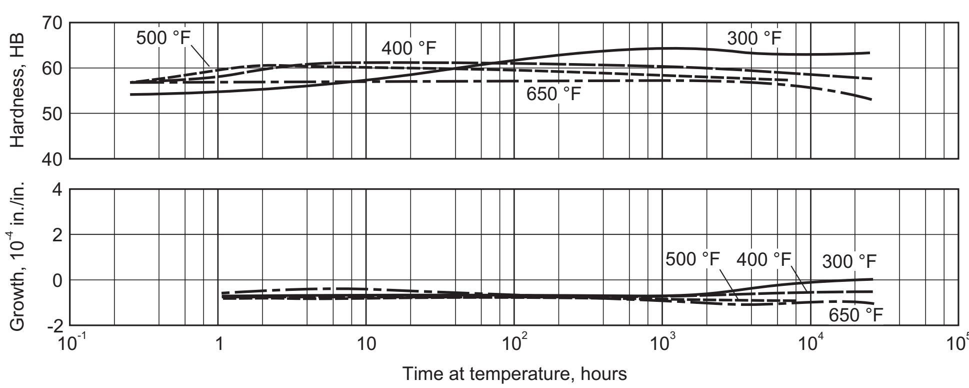

Fig. D2.37 Growth and hardness curves for aluminum alloy 514.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

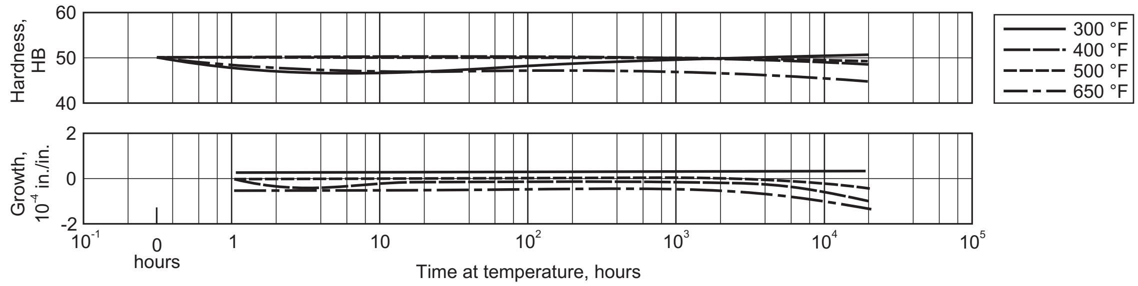

Fig. D2.38 Growth and hardness curves for aluminum alloy 514.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 825 °F, boiling water quench

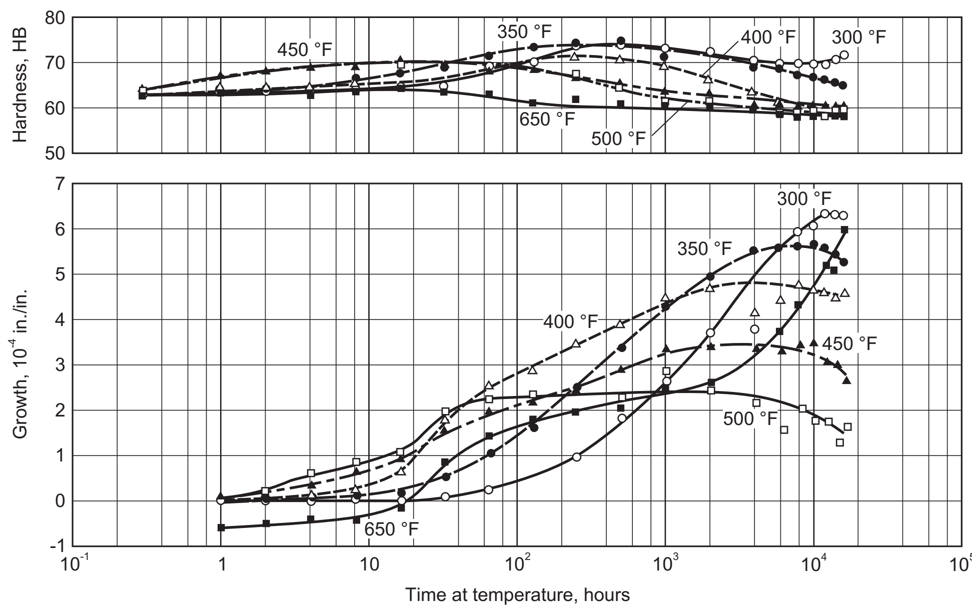

Fig. D2.39 Growth and hardness curves for aluminum alloy 516.0-F, sand cast. Specimen: 1.125 diam × 12 in. rod

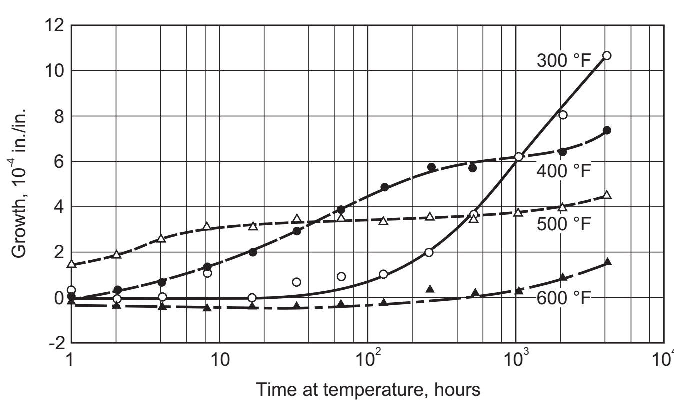

Fig. D2.40 Growth curves for aluminum alloy 518.0-F, die cast. Specimen: 3/16 in. thick plate

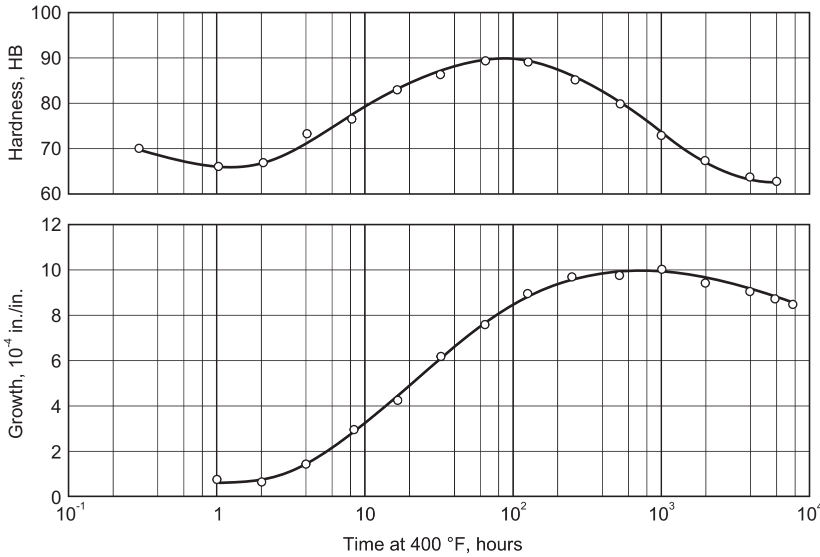

Fig. D2.41 Growth and hardness curves for aluminum alloy 520.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

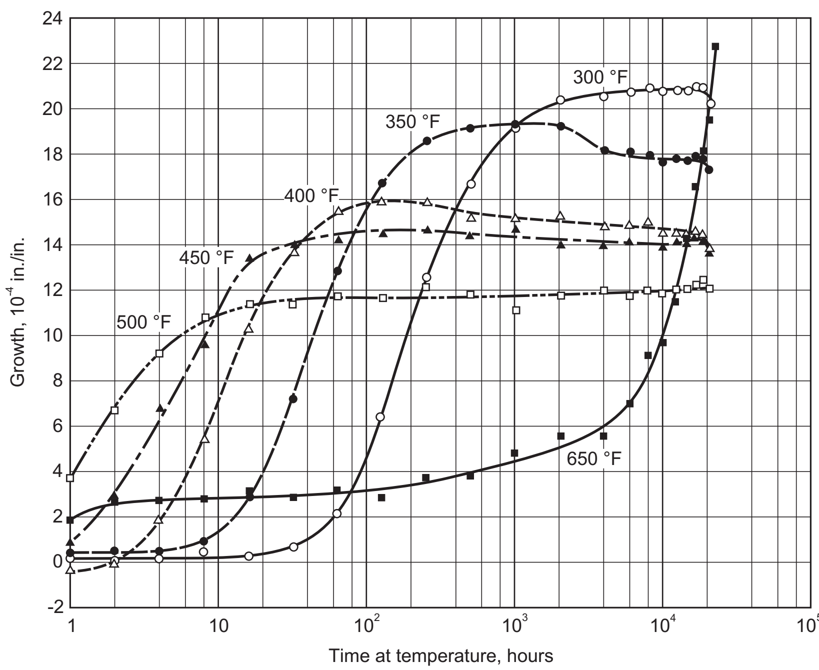

Fig. D2.42 Growth curves for aluminum alloy 520.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 825 °F, boiling water quench

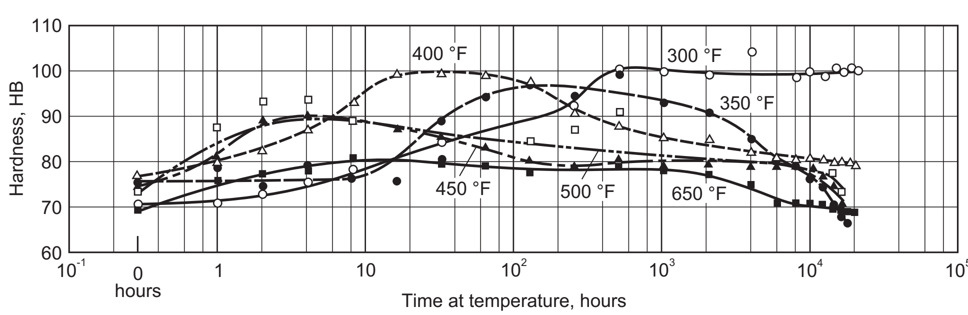

Fig. D2.43 Hardness curves for aluminum alloy 520.0-T4, permanent mold. Hardness curve. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 825 °F, boiling water quench

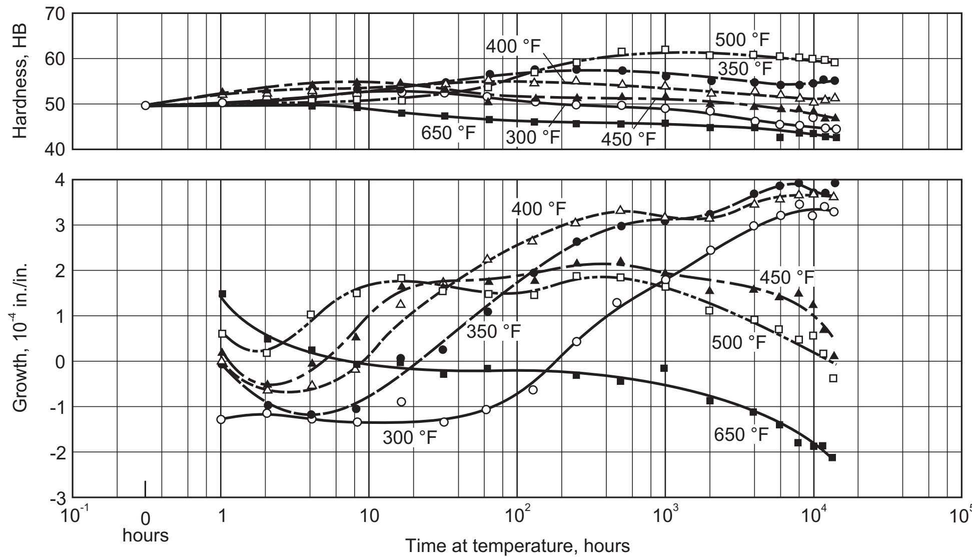

Fig. D2.44 Growth and hardness curves for aluminum alloy 850.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

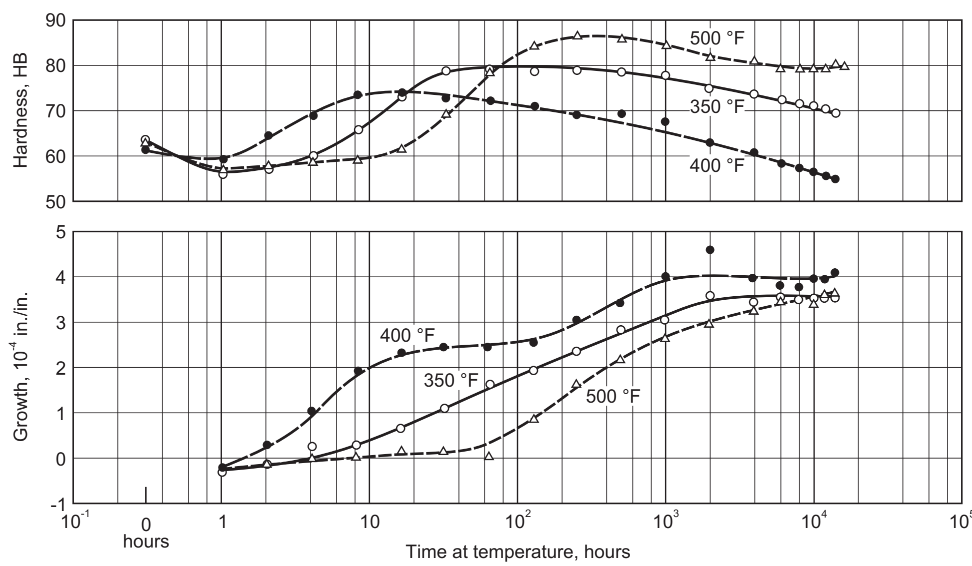

Fig. D2.45 Growth and hardness curves for aluminum alloy B850.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

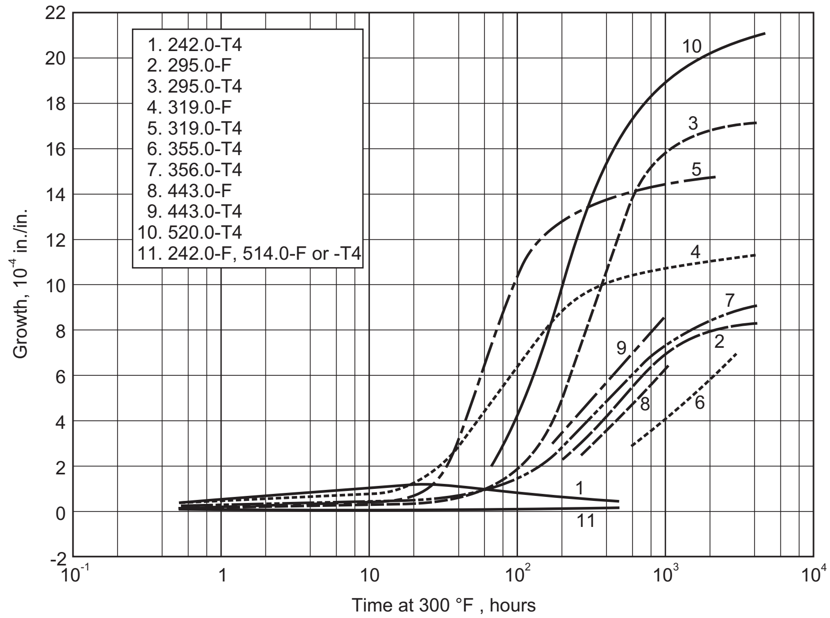

Fig. D2.46 Summary of the growth of various casting alloys at 300 °F

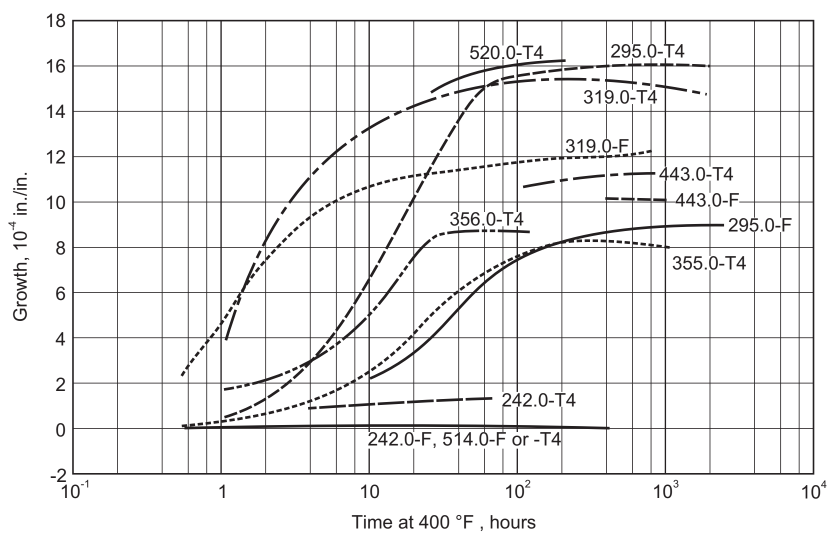

Fig. D2.47 Summary of the growth of various casting alloys at 400 °F

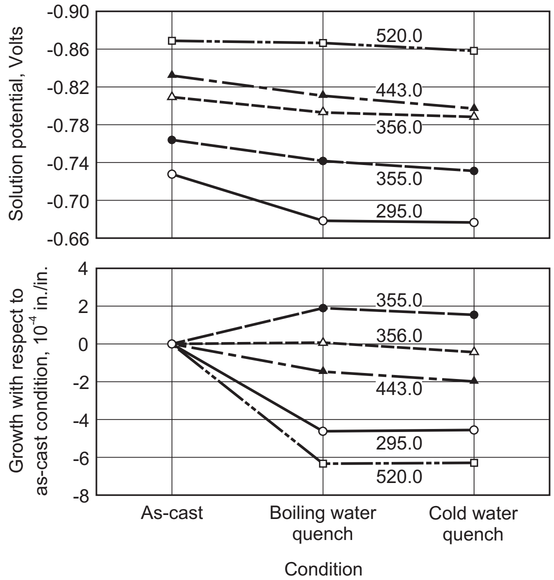

Fig. D2.48 Changes in dimension and in solution potential that occur when chill cast specimens of five aluminum alloys were given solution heat treatment

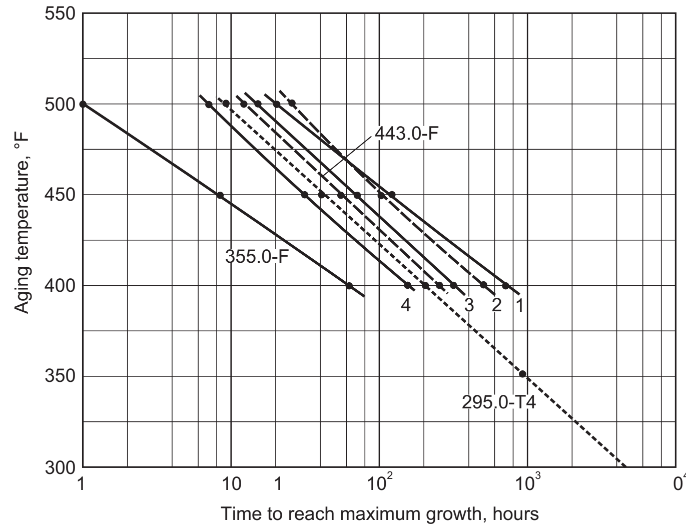

Fig. D2.49 Relationship between aging temperature and the time to reach maximum growth. Curves 1 through 4 are all 355.0. Curve 1, 940 °F, boiling water quench; curve 2, 940 °F, cold water quench; curve 3, 1000 °F, boiling water quench; curve 4, 1000 °F, cold water quench

Aluminum Alloy Castings: Properties, Processes, and Applications
J.G. Kaufman, E.L. Rooy, p 193-209
DOI:10.1361/aacp2004p193

DATA SET 3

Stress-Strain Curves

This collection of stress-strain curves is representative of the behavior of several cast alloys under tensile or compressive loads. The curves are arranged by alloy designation.

The curves are from the *Atlas of Stress-Strain Curves,* published by ASM International (Ref 1). The original source of and, when available, some background on the data are indicated on each figure.

Compressive tangent modulus curves, which represent the slope of the compressive stress-strain curve, are given for some alloys.

The effects of cyclic loading are given on several curves. The cyclic curves are constructed by connecting the points that represent the tips of stabilized hysteresis loops. The curves given indicate the occurrence of cyclic hardening.

REFERENCE

1. *Atlas of Stress-Strain Curves,* 2nd ed., ASM International, 2002, p 279–297

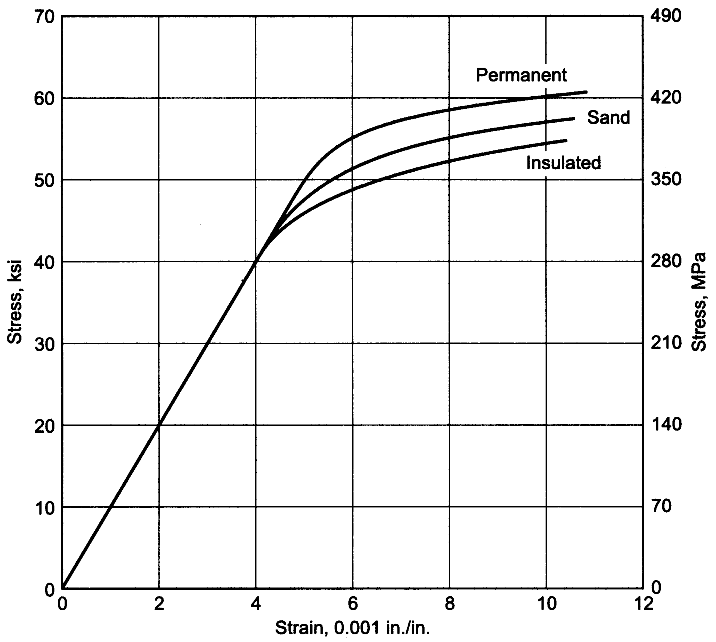

Fig. D3.1 201.0-T6 aluminum casting, tensile stress-strain curves, various casting processes

Effect of casting process. Heat treatment: 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 20 h at 154 °C (310 °F), air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 450 MPa (65.2 ksi); tensile yield strength, 402 MPa (58.3 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 394 MPa (57.1 ksi); tensile yield strength, 372 MPa (53.9 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 359 MPa (52.1 ksi); tensile yield strength, 349 MPa (50.6 ksi). UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 67

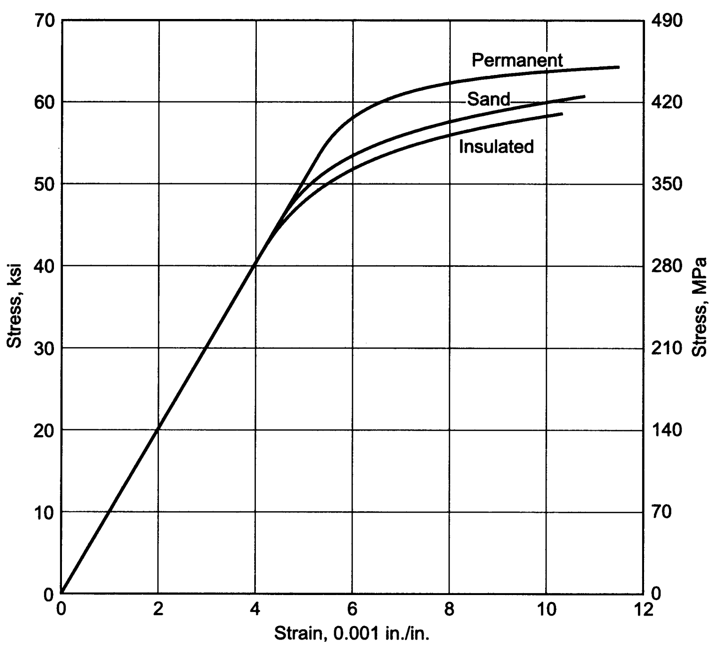

Fig. D3.2 201.0-T6 aluminum casting, compressive stress-strain curves, various casting processes

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 20 h at 154 °C (310 °F), air cooled. Average compressive yield strength: permanent mold castings, 433 MPa (62.8 ksi); sand castings, 396 MPa (57.5 ksi); insulated mold castings, 382 MPa (55.4 ksi). UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 67

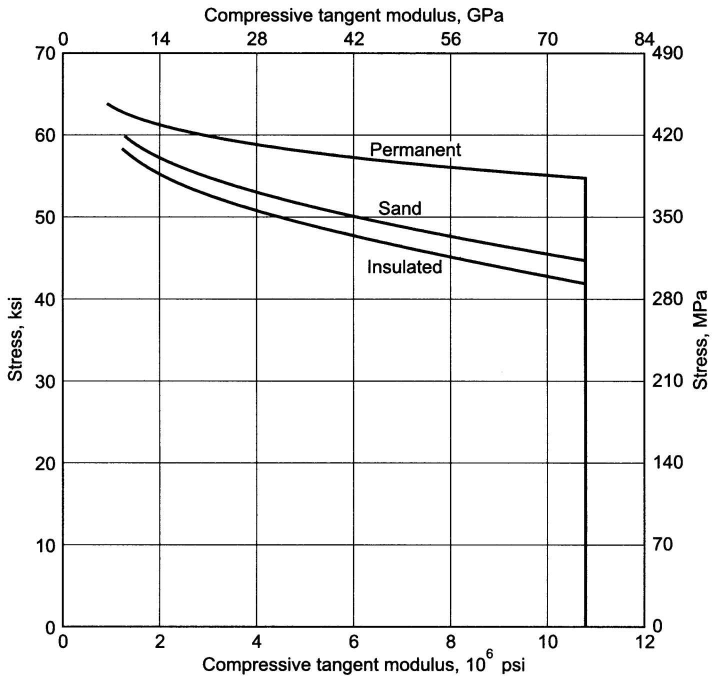

Fig. D3.3 201.0-T6 aluminum casting, compressive tangent modulus curves, various casting processes

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 20 h at 154 °C (310 °F), air cooled. UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 68

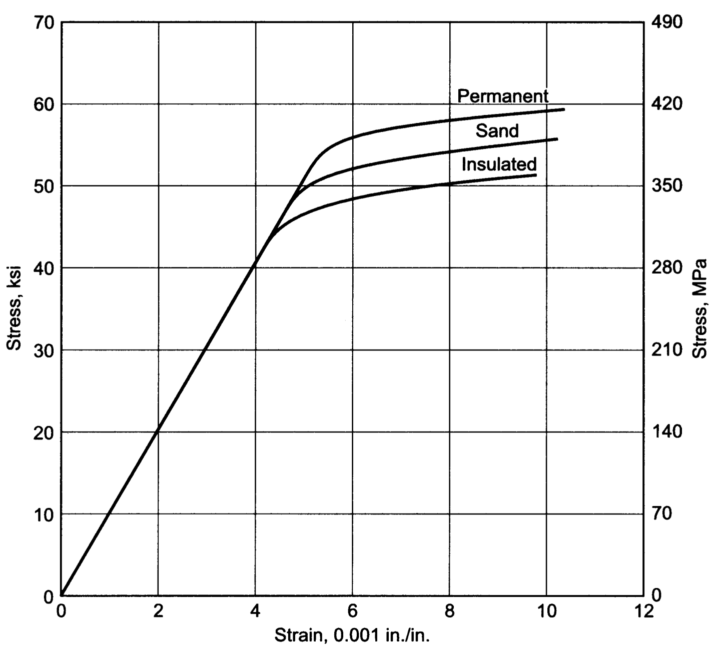

Fig. D3.4 201.0-T7 aluminum casting, tensile stress-strain curves, various casting processes

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 5 h at 188 °C (370 °F), air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 439 MPa (63.7 ksi); tensile yield strength, 403 MPa (58.5 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 385 MPa (55.8 ksi); tensile yield strength, 374 MPa (54.2 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 345 MPa (50.6 ksi); tensile yield strength, 344 MPa (49.9 ksi). UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 67

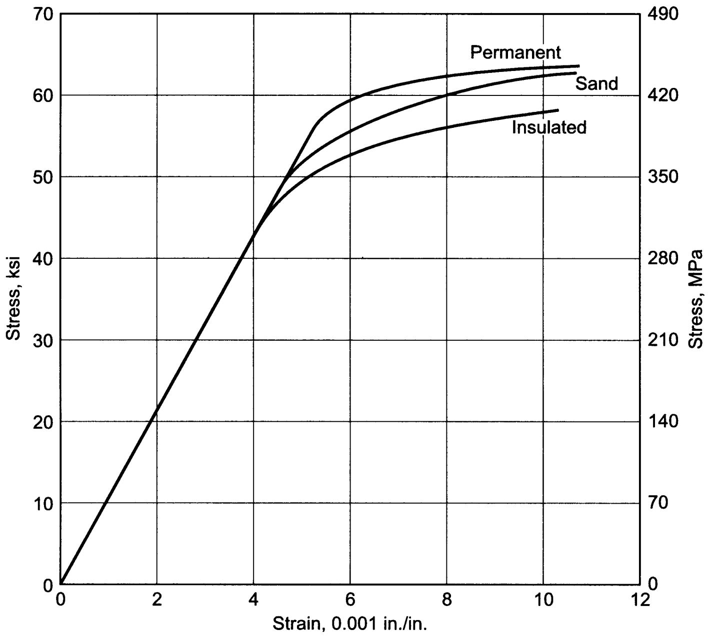

Fig. D3.5 201.0-T7 aluminum casting, compressive stress-strain curves, various casting processes

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 5 h at 188 °C (370 °F), air cooled. Average compressive yield strength: permanent mold castings, 429 MPa (62.2 ksi); sand castings, 407 MPa (59.1 ksi); insulated mold castings, 377 MPa (54.7 ksi). UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 67

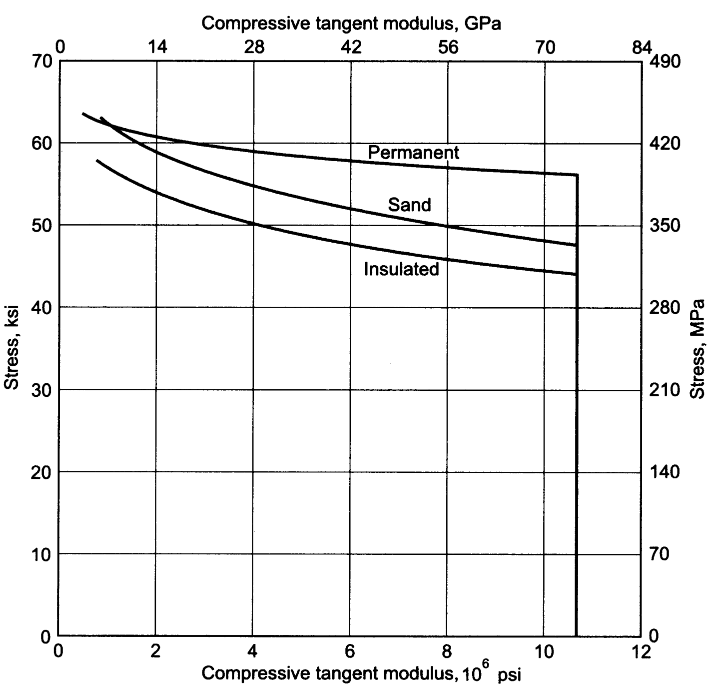

Fig. D3.6 201.0-T7 aluminum casting, compressive tangent modulus curves, various casting processes

Effect of casting process is illustrated. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 5 h at 188 °C (370 °F), air cooled. UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 68

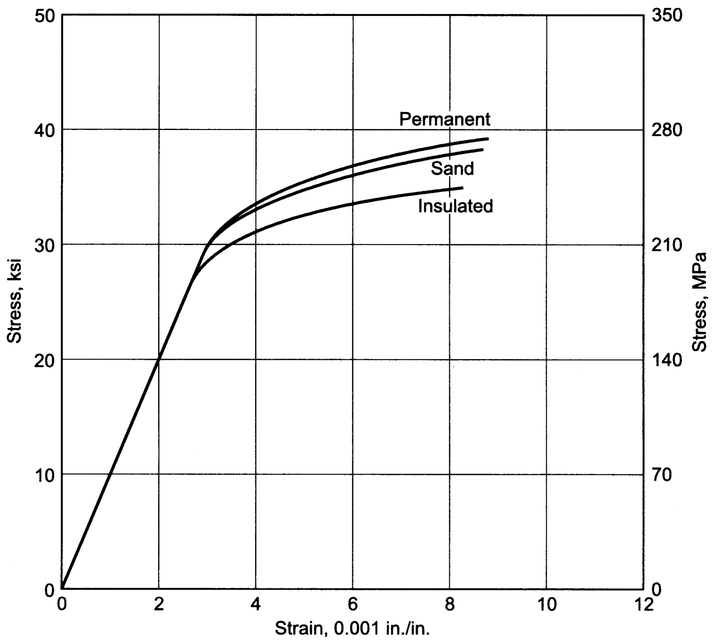

Fig. D3.7 201.0-T43 aluminum casting, tensile stress-strain curves, various casting processes

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 0.5 h at 154 °C (310 °F), air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 407 MPa (59.0 ksi); tensile yield strength, 250 MPa (36.2 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 356 MPa (51.7 ksi); tensile yield strength, 243 MPa (35.3 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 273 MPa (39.6 ksi); tensile yield strength, 225 MPa (32.6 ksi). UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 67

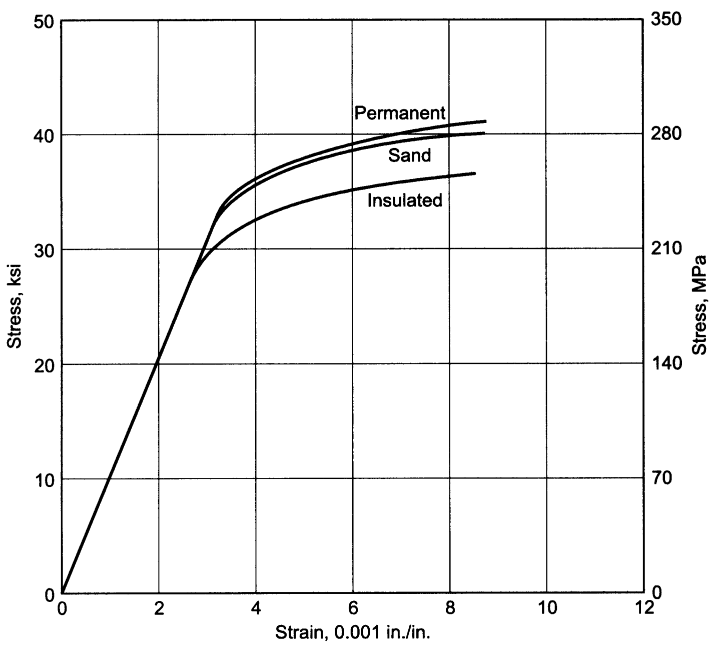

Fig. D3.8 201.0-T43 aluminum casting, compressive stress-strain curves, various casting processes

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 0.5 h at 154 °C (310 °F), air cooled. Average compressive yield strength: permanent mold castings, 272 MPa (39.4 ksi); sand castings, 266 MPa (38.6 ksi); insulated mold castings, 238 MPa (34.5 ksi). UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 67

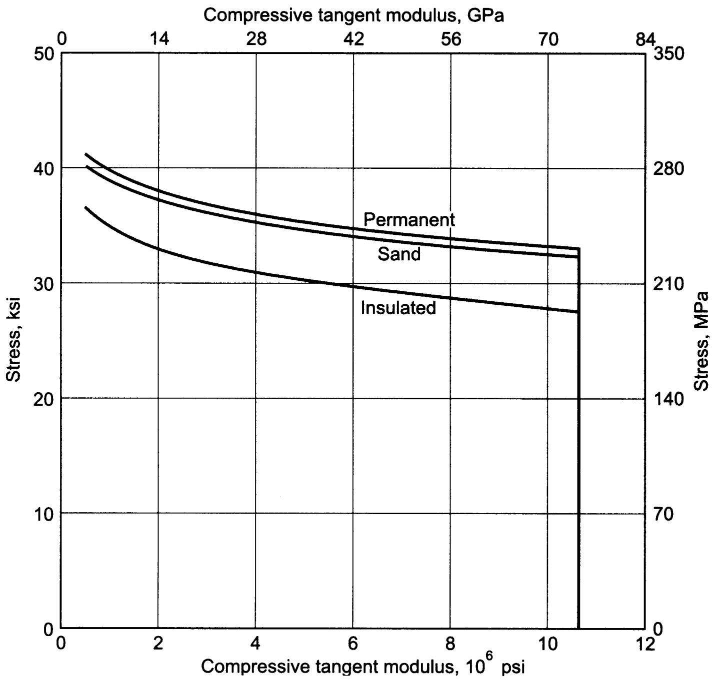

Fig. D3.9 201.0-T43 aluminum casting, compressive tangent modulus curves, various casting processes

Effect of casting process is illustrated. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 0.5 h at 154 °C (310 °F), air cooled. UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 68

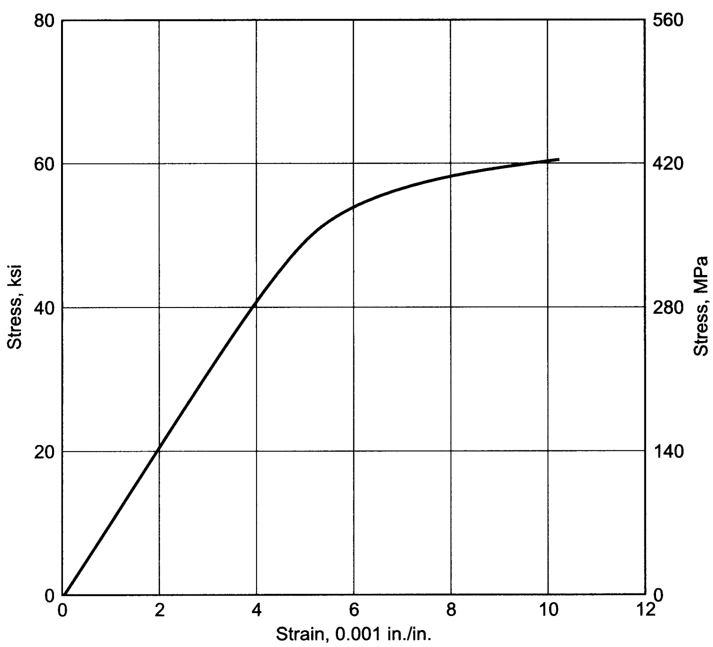

Fig. D3.10 A201.0-T7 aluminum casting, typical tensile stress-strain curve

Designated area, at room temperature. Ramberg-Osgood parameter, *n*(tension) = 14. S basis design properties (originally presented in ksi) for strength class 1 and 2, designated area within casting: ultimate tensile strength, 414 MPa (60 ksi); tensile yield strength, 345 MPa (50 ksi); compressive yield strength, 352 MPa (51 ksi). UNS A12010

Source: *MIL-HDBK-5H,* Dec 1998, p 3-463, 3-465

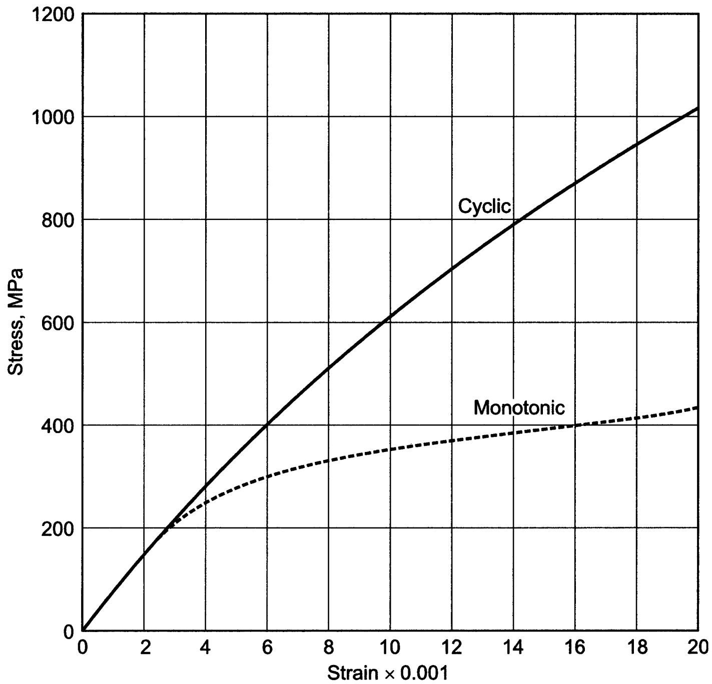

Fig. D3.11 242.0-T5 aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic

Al-Cu-Ni-Mg system. Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices. UNS A02420

Source: John Deere Materials Data, Deere & Co., Moline, IL, p C13

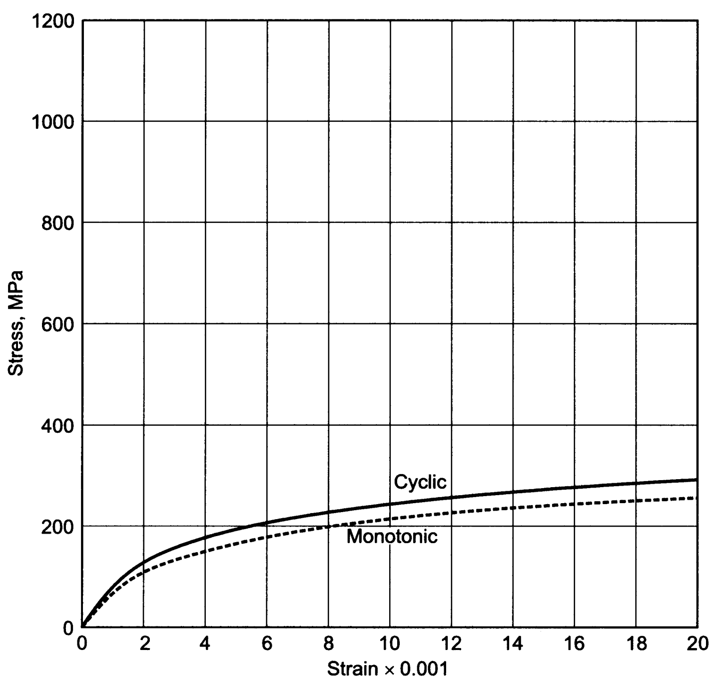

Fig. D3.12 A332.0-T5 (PC) aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic

Al-Si-Ni-Mg system. Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices. UNS A13320 replaced by UNS A03360

Source: John Deere Materials Data, Deere & Co., Moline, IL, p D14

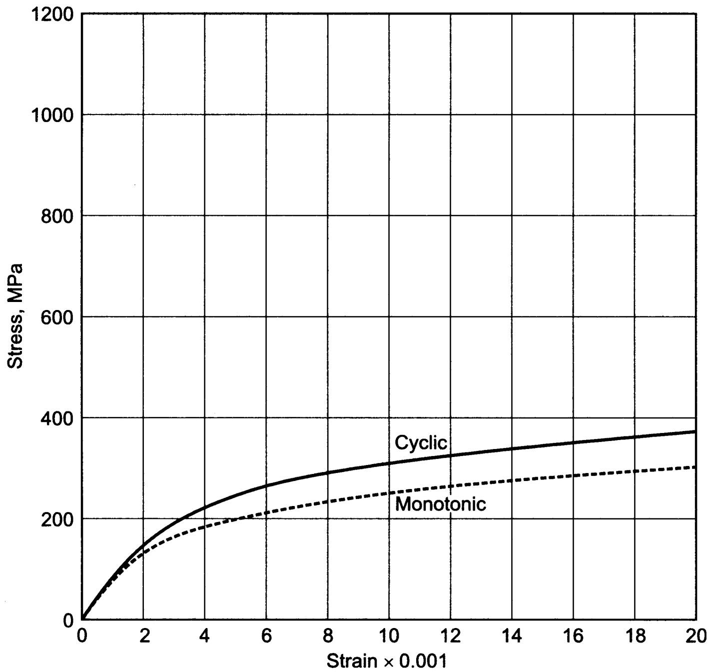

Fig. D3.13 E332.0-T5 aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic

Al-Si-Ni-Mg system. Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices

Source: John Deere Materials Data, Deere & Co., Moline, IL, p F13

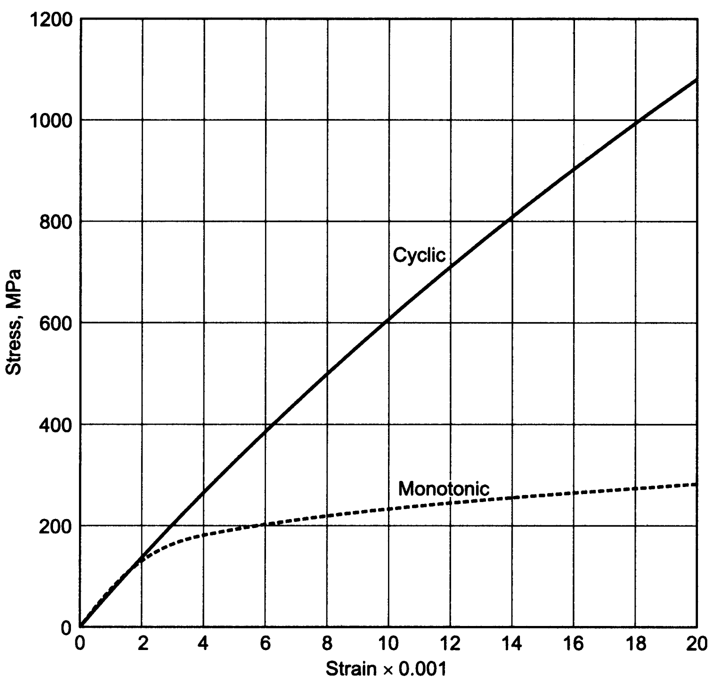

Fig. D3.14 F332.0-T5 (SR) aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic

Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices. UNS A63320 replaced by UNS A03320

Source: John Deere Materials Data, Deere & Co., Moline, IL, p A14

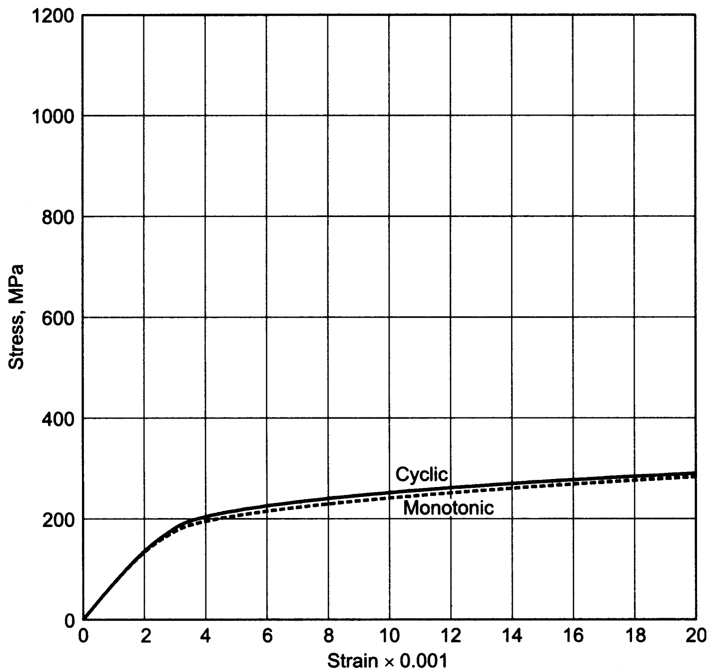

Fig. D3.15 354.0-T5 aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic

354.0-T5 casting material, Al-Si-Cu-Mg system. Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices. UNS A03540

Source: John Deere Materials Data, courtesy of Deere & Co., Moline, IL, p E12

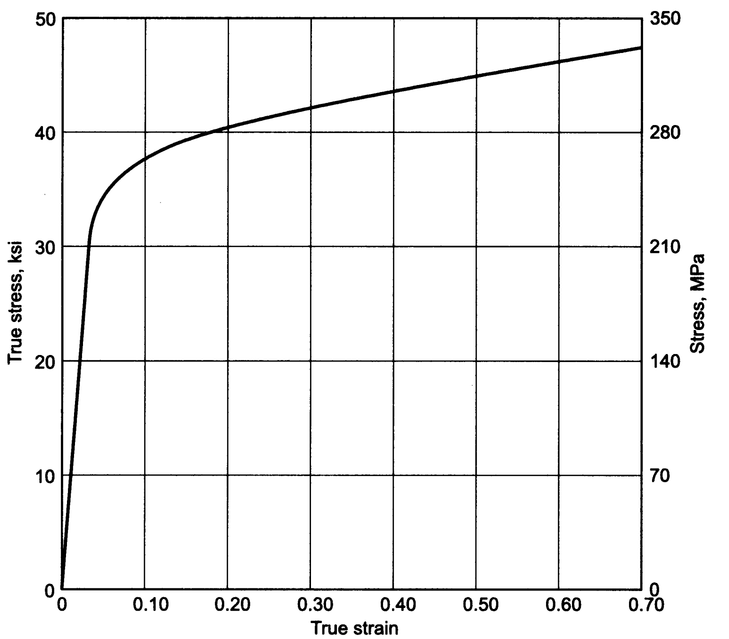

Fig. D3.16 C355.0-T61 aluminum casting, tensile uniaxial true stress-strain curve

Specimen size: 6.25 mm (0.250 in.) diam, 31.75 mm (1.25 in.) gage length. UNS A33550

Source: J. Mattavi, "Low Cycle Fatigue Behavior Under Biaxial Strain Distribution," TP-67-16-T, Hamilton Standard, Sept 1967. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 70

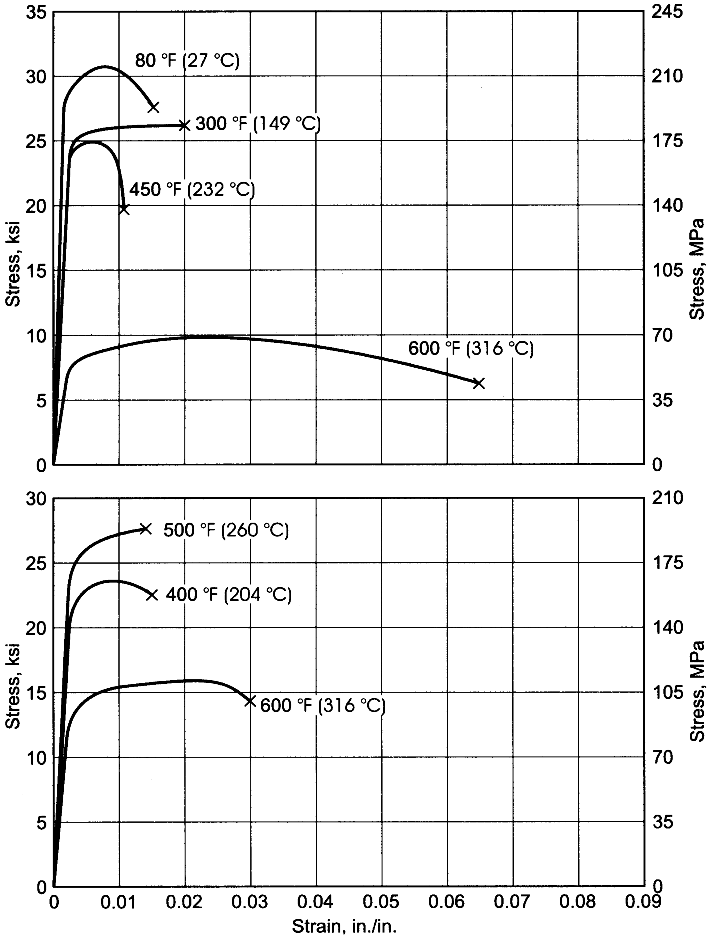

Fig. D3.17 356.0-T6 aluminum casting, tensile stress-strain curves at several temperatures

Effect of strain rate and temperature. Strain rate is 1.0 s^{-1}. Hold times at given temperatures: 1800 s (top); 10 s (bottom). Material was solution heat treated at 540 °C (1000 °F), water quenched, and aged at 154 °C (310 °F) for 3 h. UNS A03560

Source: H.E. Dedman, E.J. Wheelan, and E.J. Kattus, "Tensile Properties of Aircraft-Structural Metals at Various Rates of Loading after Rapid Heating," WADC TR-58-440, Southern Research Institute, Part 1, Nov 1958. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 2, CINDAS/Purdue University, 1994, p 71

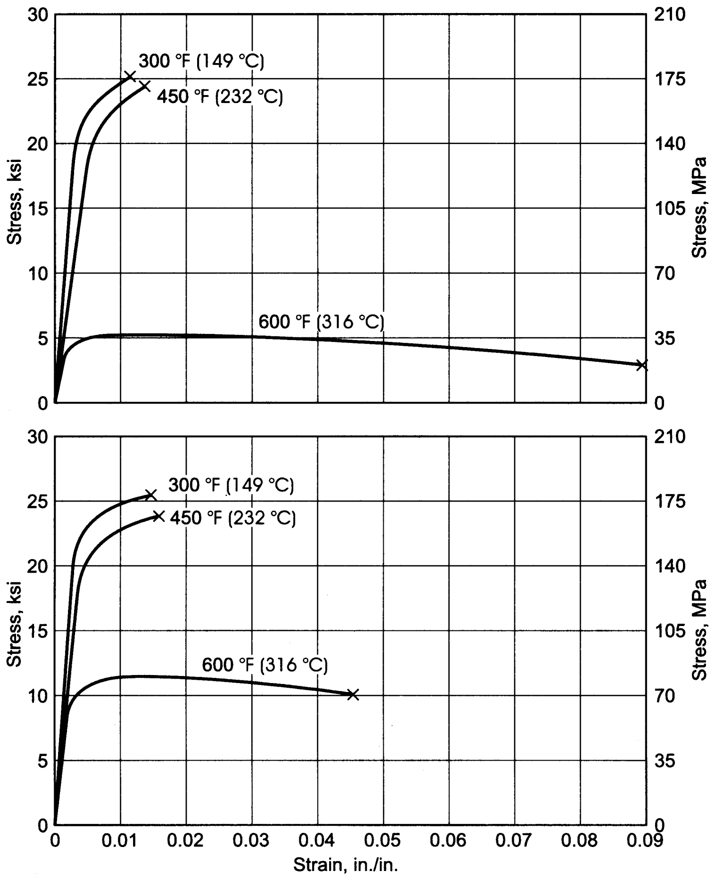

Fig. D3.18 356.0-T6 aluminum casting, tensile stress-strain curves at several temperatures

Effect of strain rate and temperature. Strain rate is 0.01 s^{-1}. Hold times at given temperatures: 1800 s (top); 10 s (bottom). Material was solution heat treated at 540 °C (1000 °F), water quenched, and aged at 154 °C (310 °F) for 3 h. UNS A3560

Source: H.E. Dedman, E.J. Wheelan, and E.J. Kattus, "Tensile Properties of Aircraft-Structural Metals at Various Rates of Loading after Rapid Heating," WADC TR-58-440, Southern Research Institute, Part 1, Nov 1958. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 2, CINDAS/Purdue University, 1994, p 71

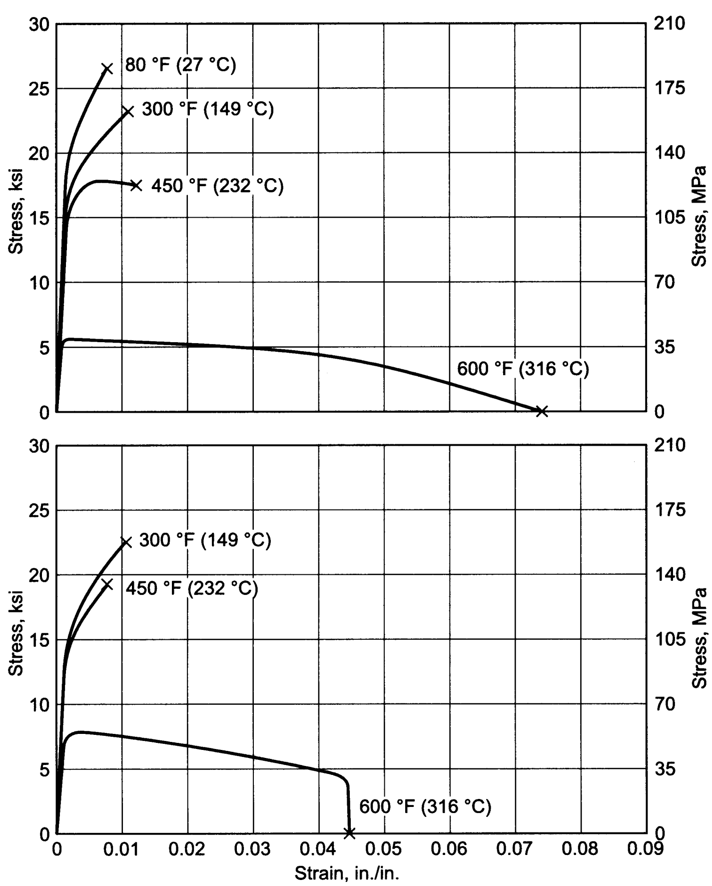

Fig. D3.19 356.0-T6 aluminum casting, tensile stress-strain curves at several temperatures

Effect of strain rate and temperature. Strain rate is 0.00005 s^{-1}. Hold times at given temperatures: 1800 s (top); 10 s (bottom). Material was solution heat treated at 540 °C (1000 °F), water quenched, and aged at 154 °C (310 °F) for 3 h. UNS A03560

Source: H.E. Dedman, E.J. Wheelan, and E.J. Kattus, "Tensile Properties of Aircraft-Structural Metals at Various Rates of Loading after Rapid Heating," WADC TR-58-440, Southern Research Institute, Part 1, Nov 1958. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 2, CINDAS/Purdue University, 1994, p 71

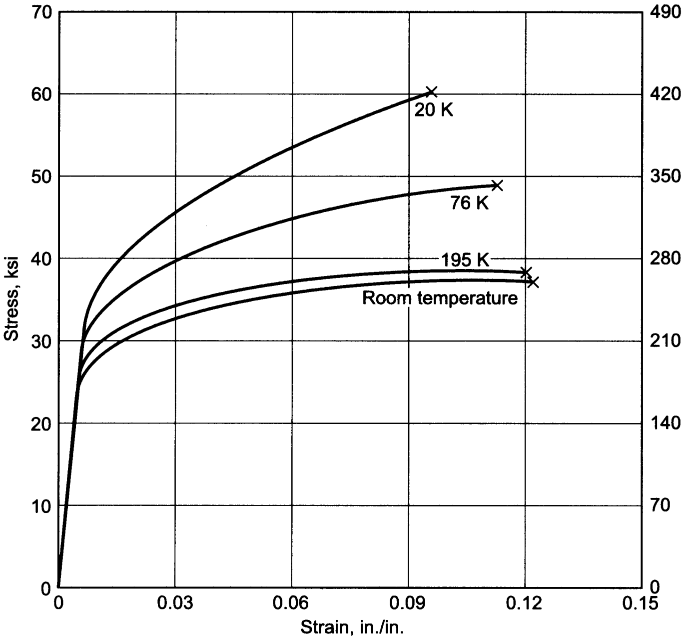

Fig. D3.20 356.0-T6 aluminum casting, tensile stress-strain curves at low temperature

Chill cast aluminum. Hardness, 41 HRB. UNS A03560

Source: K.A. Warren and R.P. Reed, *Tensile and Impact Properties of Selected Materials from 20 to 300 K,* Monograph 63, National Bureau of Standards, June 1963. As published in *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 70

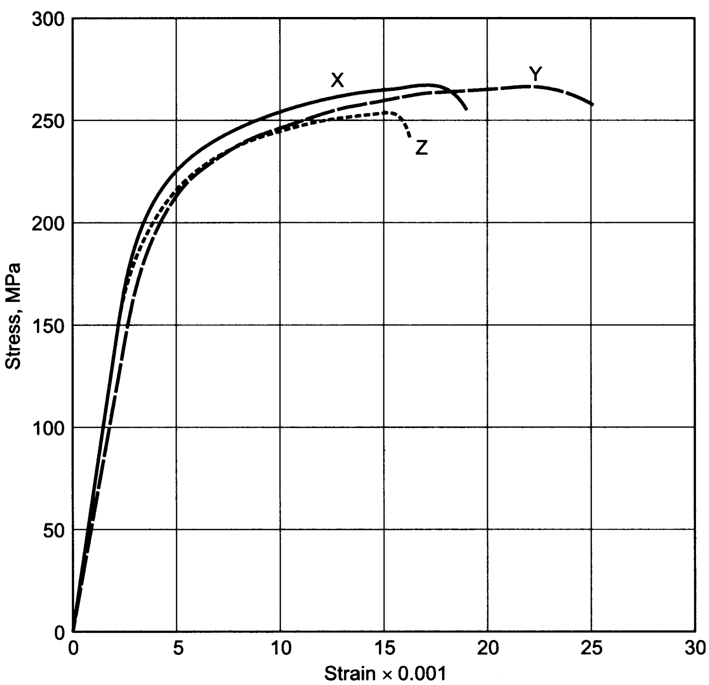

Fig. D3.21 A356-T6 aluminum cast cylinder, monotonic tensile stress-strain curves

Near-net-shape casting formed by pouring molten alloy, 704 °C (1300 °F) into investment molds at room temperature (X), 538 °C (1000 °F) (Y), and 982 °C (1800 °F) (Z). Three different cooling rates create different microstructures. Curves are results from one laboratory. Property values are averages from seven labs as part of a round-robin test program. Young's modulus, GPa (psi $\times 10^6$), X, 70 (10.1), Y, 70 (10.1), Z, 71 (10.3); yield strength 0.2% offset, MPa (ksi), X, 229 (33.3), Y, 224 (32.5), Z, 217 (31.5); ultimate strength MPa (ksi), X, 283 (41.1), Y, 266 (38.6), Z, 252 (36.6); strain hardening exponent (n), X, 0.083, Y, 0.087, Z, 0.091; strain-hardening coefficient K, MPa (ksi), X, 388 (56.4), Y, 397 (57.6), Z, 382 (55.4). UNS A13560

Source: *Fatigue and Fracture Toughness of A356-T6 Cast Aluminum Alloy,* R.I. Stephens, Ed., SP-760, Society of Automotive Engineers, 1988

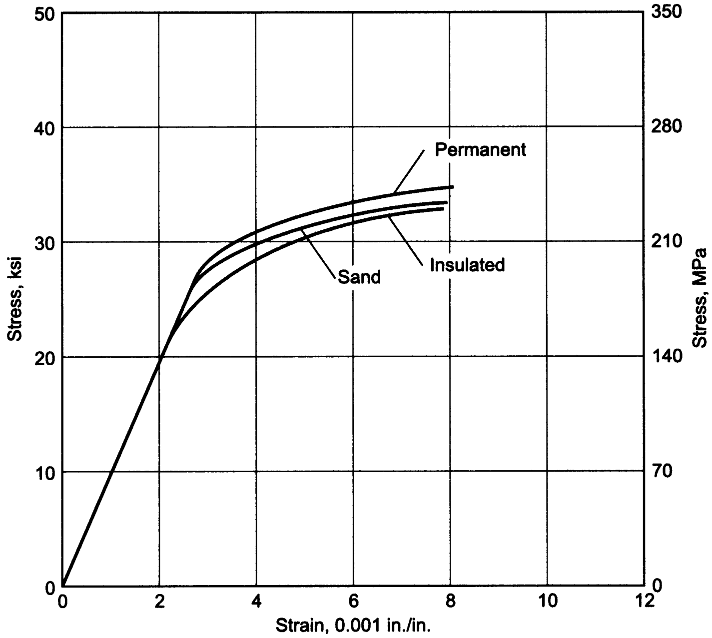

Fig. D3.22 A356.0-T6 aluminum casting, tensile stress-strain curves, various casting processes

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 3 h at 154 °C (310 °F), and air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 299 MPa (43.4 ksi); tensile yield strength, 215 MPa (31.2 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 253 MPa (36.7 ksi); tensile yield strength, 223 MPa (32.3 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 219 MPa (31.7 ksi); tensile yield strength, 205 MPa (29.8 ksi). UNS A13560

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 66

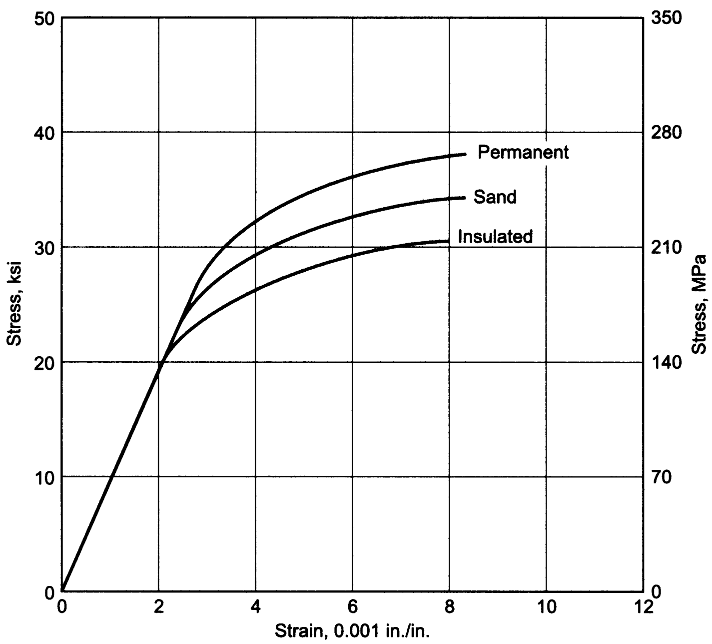

Fig. D3.23 A356.0-T6 aluminum casting, compressive stress-strain curves, various casting processes

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 3 h at 154 °C (310 °F), and air cooled. Average compressive yield strength: permanent mold castings, 219 MPa (31.7 ksi); sand castings, 245 MPa (35.6 ksi); insulated mold castings, 192 MPa (27.9 ksi). UNS A13560

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 66

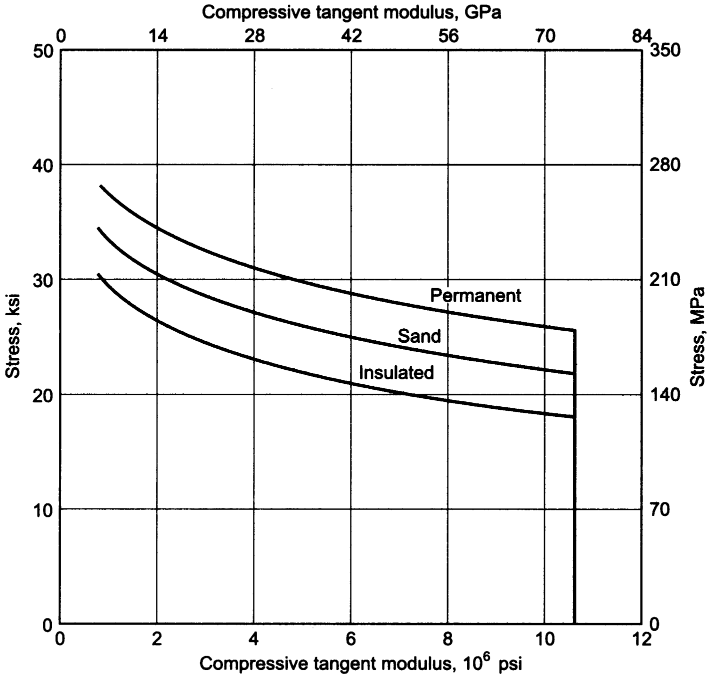

Fig. D3.24 A356.0-T6 aluminum casting, compressive tangent modulus curves, various casting processes

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 3 h at 154 °C (310 °F), and air cooled. UNS A13560

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 68

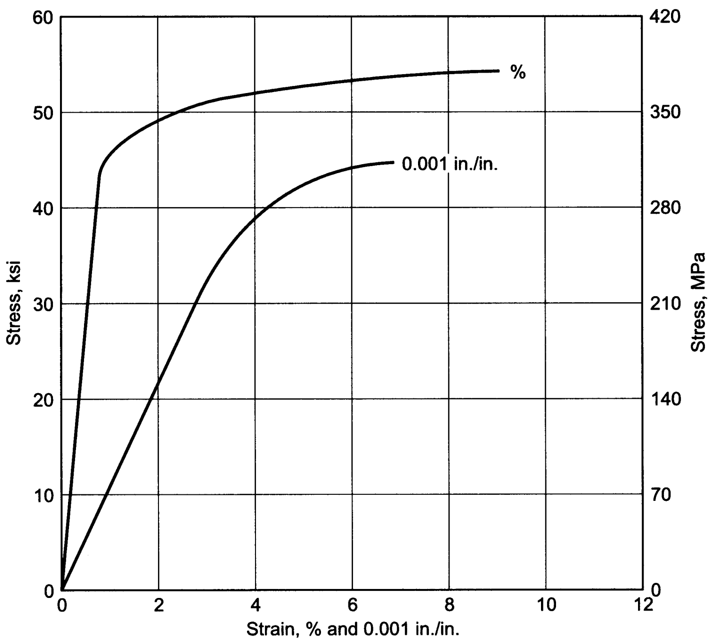

Fig. D3.25 A357.0-T6 aluminum cast plate, tensile stress-strain curves

Sand cast plate thickness: 6.35 mm (0.25 in.). The full range strain is given in percent (%) (top curve) and the expanded range strain is in 0.001 in./in. (bottom curve). Composition: Al-7.0Si-0.6Mg-0.1Te-Be. UNS A13570

Source: "Development: Premium Alloy Castings of Alloy A357.0-T6," Alcoa, Pittsburgh, PA, 1971. As published in *Aerospace Structural Metals Handbook,* Vol 5, Code 3109, CINDAS/USAF CRDA Handbooks Operation, Purdue University, 1995, p 24

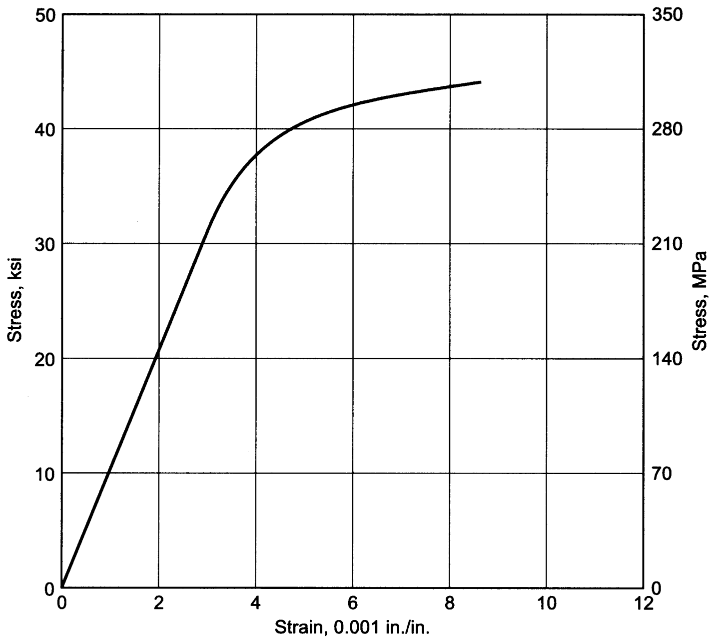

Fig. D3.26 A357.0T6 aluminum casting, typical tensile stress-strain curve

Class 2 alloy casting, designated area, at room temperature. Ramberg-Osgood parameter, *n*(tension) = 16. S basis design properties (originally presented in ksi) for strength class 2, designated area within casting: ultimate tensile strength, 345 MPa (50 ksi); tensile and compressive yield strength, 276 MPa (40 ksi). UNS A13570

Source: *MIL-HDBK-5H,* Dec 1998, p 3-485, 3-486

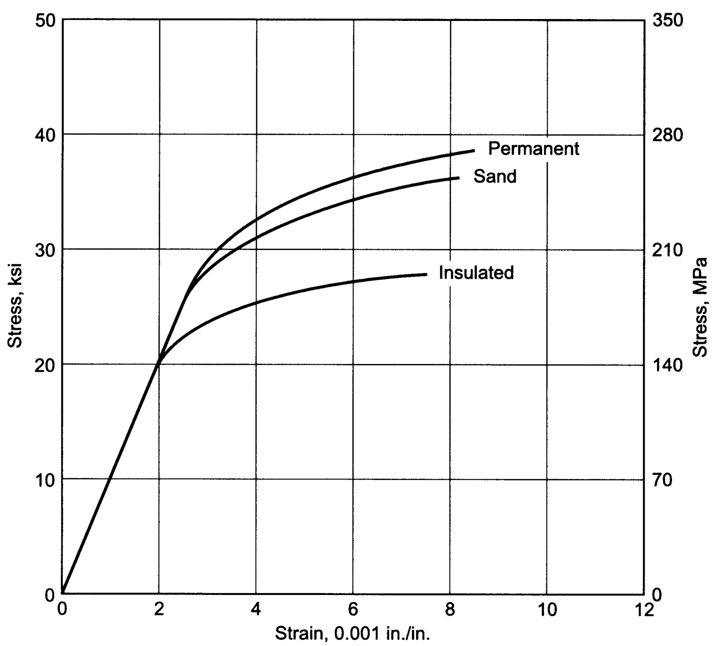

Fig. D3.27 A357.0-T6 aluminum casting, tensile stress-strain curves, various casting processes

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 5 h at 177 °C (350 °F), and air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 316 MPa (45.8 ksi); tensile yield strength, 243 MPa (35.2 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 268 MPa (38.9 ksi); tensile yield strength, 229 MPa (33.2 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 179 MPa (26.0 ksi); tensile yield strength, 179 MPa (26.0 ksi). UNS A13570

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 66

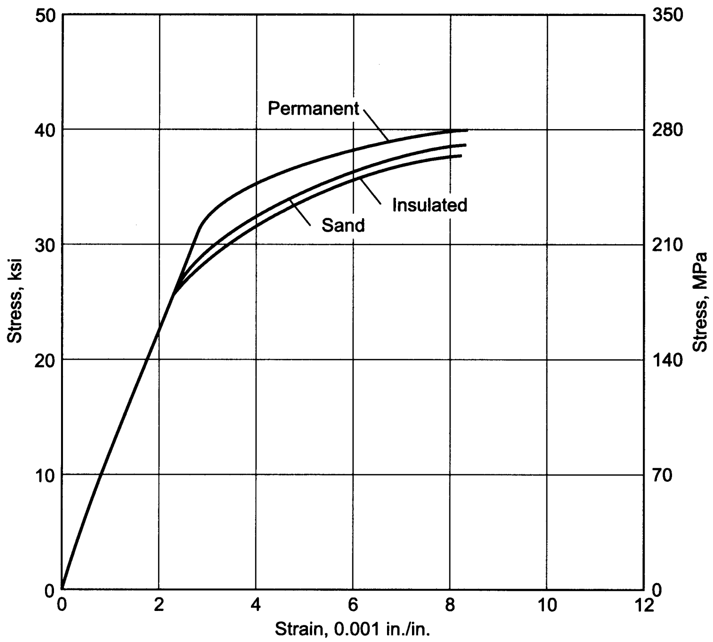

Fig. D3.28 A357.0-T6 aluminum casting, compressive stress-strain curves, various casting processes

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 5 h at 177 °C (350 °F), and air cooled. Average compressive yield strength: permanent mold castings, 256 MPa (37.2 ksi); sand castings, 240 MPa (34.8 ksi); insulated mold castings, 232 MPa (33.7 ksi). UNS A13570

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 66

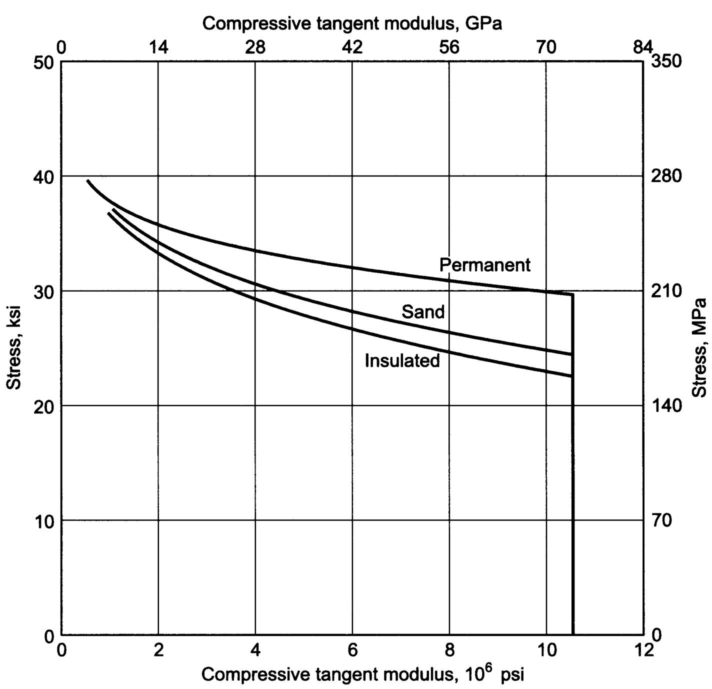

Fig. D3.29 A357.0-T6 aluminum casting, compressive tangent modulus curves, various casting processes

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 5 h at 177 °C (350 °F), and air cooled. UNS A13570

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook,* Vol 3, CINDAS/Purdue University, 1994, p 24, 68

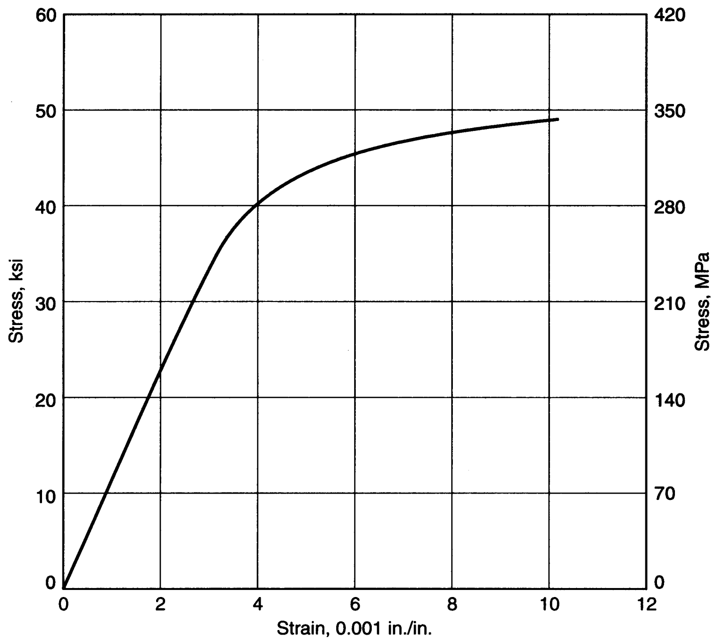

Fig. D3.30 A357.0-T6 aluminum cast plate, compressive stress-strain curve

Sand cast plate thickness: 6.35 mm (0.25 in.). Composition: Al-7.0Si-0.6Mg-0.1Te-Be. UNS A13570

Source: "Development: Premium Alloy Castings of Alloy A357.0-T6," Alcoa, Pittsburgh, PA, 1971. As published in *Aerospace Structural Metals Handbook,* Vol 5, Code 3109, CINDAS/USAF CRDA Handbooks Operation, Purdue University, 1995, p 29

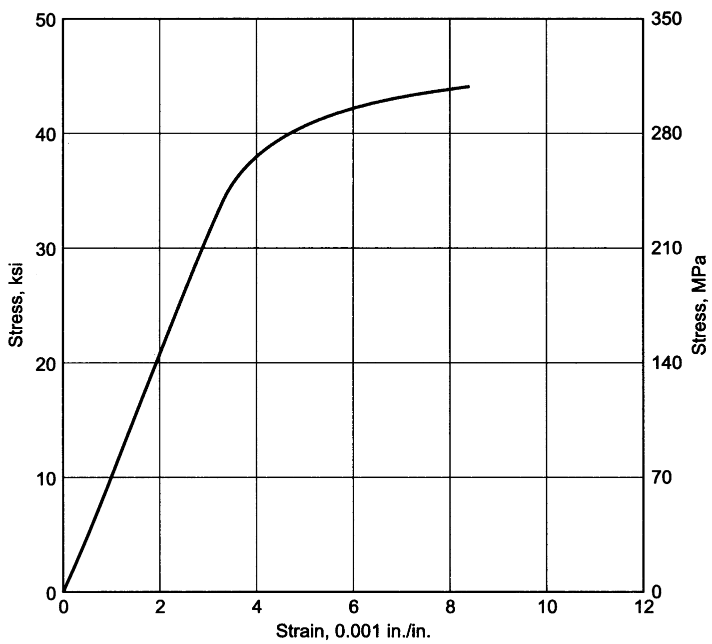

Fig. D3.31 D357.0-T6 aluminum casting, typical tensile stress-strain curve

Designated area, at room temperature. Ramberg-Osgood parameter, *n*(tension) = 16. B basis design properties (originally presented in ksi) for designated area within casting: ultimate tensile strength, 338 MPa (49 ksi); tensile and compressive yield strength, 285 MPa (41 ksi). UNS A43570

Source: *MIL-HDBK-5H,* Dec 1998, p 3-488, 3-489

Aluminum Alloy Castings: Properties, Processes, and Applications
J.G. Kaufman, E.L. Rooy, p 211-242
DOI:10.1361/aacp2004p211

DATA SET 4

Tensile Properties at High and Low Temperatures and at Room Temperature after High-Temperature Exposure

This data set contains the results of uniaxial tensile tests of a wide range of aluminum casting alloys conducted at:

- High temperatures from 212 to 700 °F (100 to 370 °C) after various holding times at the testing temperature
- Subzero temperatures from –452 to –18 °F (–269 to –28 °C) after one-half hour at the testing temperature (holding time at subzero temperatures has no effect on properties)
- Room temperature after holding at high temperatures from 212 to 700 °F (100 to 370 °C)

These data were developed at the Alcoa Research Laboratories in New Kensington, PA, over the period of years from 1950 to the present time. The early generation and analysis of the data was led by Kenneth O. Bogardus and Robert C. Malcolm, Jr., with principal testing support from Robert C. Faulk and George Schofield. In more recent years, the activity has been led by Robert J. Bucci and Daniel Lege. Most of the data included here were originally published in Ref 1, although some additional data have been added for this publication.

The tensile tests were made in accordance with ASTM E 8 and E 21, with 0.5 in. (12.5 mm) diam tensile specimens per Appendix 3, Fig. A3.1. In most cases, the specimens were as-cast test bars. Yield strengths were measured at 0.2% offset using autographic extensometers; in the tests at high and low temperatures, the extensometers were used in conjunction with strain-transfer devices. In the case of tests made at subzero temperatures, the low temperatures were achieved by immersion of the specimens in the following liquids for one-half hour prior to and during the tests:

- −18 °F (–28 °C), dry ice and alcohol
- −112 °F (–80 °C), liquefied petroleum gas
- −320 °F (–196 °C), liquefied nitrogen
- −452 °F (–269 °C), liquefied helium

In most cases, tests were made of several lots of material of each alloy and temper. The results for the several lots were then analyzed together graphically and statistically, and the averages normalized to the room-temperature typical values; in these cases, the values are identified as "typical values" in the table. In some cases, too few data, perhaps only for a single lot, were available, and so these are reported as "representative" values (raw data) rather than as typical values.

REFERENCES

1. J.G. Kaufman, Ed., *Properties of Aluminum Alloys: Tensile, Creep and Fatigue Data at High and Low Temperatures,* ASM International, 1999
2. J.H. Belton, L.L. Godby, and B.L. Taft, *Materials for Use at Liquid Hydrogen Temperature,* STP 287, ASTM, 1960

Table D4.1 201.0-T7 Sand castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4*D*, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4*D*, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
−452	−269	...	93	640	81	560	7	...	...	...	...	...	...	...
−423	−253	...	93	640	79	545	8	...	...	...	...	...	...	...
−320	−196	...	89	615	67	460	8	...	...	...	...	...	...	...
−112	−80	...	77	530	70	485	6	...	...	...	...	...	...	...
−18	−28	...	74	510	87	600	6	...	...	...	...	...	...	...
75	25	...	72	495	65	450	6	10.3	71	72	495	65	450	6
300	150	100	64	440	57	395	9	...	...	72	495	65	450	6
		1,000	60	415	54	370	10	...	...	70	485	61	420	6
		10,000	58	400	52	360	6	...	...	68	470	58	400	4
350	177	100	54	370	49	340	10	...	...	68	470	61	420	4
		1,000	51	350	46	315	8	...	...	63	435	57	395	4
		10,000	43	295	37	255	9	...	...	58	400	45	310	6
400	205	100	48	330	42	290	10	...	...	66	455	58	400	5
		1,000	39	270	33	230	16	...	...	55	380	44	305	4
		10,000	24	165	18	125	25	...	...	41	285	22	150	12
450	230	1,000	22	150	15	105	25	...	...	41	285	22	150	12
		10,000	19	130	13	90	25	...	...	37	255	18	125	13
500	260	1,000	16	110	13	90	25	...	...	38	260	20	140	12
		10,000	14	95	10	70	32	...	...	34	235	17	115	11
600	315	1,000	9.0	62	8.0	55	48	...	...	34	235	14	95	12
		10,000	8.0	55	6.0	41	51	...	...	29	200	11	75	13

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.2 224.0-T7 Sand and permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4*D*, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4*D*, %
F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
75	25		61	420	48	330	4	10.5	72	61	420	48	330	4
300	150	0.1	53	365	42	290	7	...	...	...	...	...	...	...
		0.5	53	365	41	285	7	...	...	...	...	...	...	...
		100	53	365	41	285	5	...	...	62	425	49	340	4
		1,000	53	365	38	260	6	...	...	61	420	44	305	4
		10,000	49	340	37	255	5	...	...	61	420	42	290	5
350	177	0.1	48	330	41	285	10	...	...	...	...	...	...	...
		0.5	48	330	41	285	10	...	...	...	...	...	...	...
		100	47	325	37	255	7	...	...	63	435	45	310	5
		1,000	43	295	32	220	11	...	...	58	400	38	260	5
		10,000	43	295	31	215	10	...	...	55	380	38	260	4
400	205	0.1	43	295	37	255	14	...	...	...	...	...	...	...
		0.5	42	290	36	250	14	...	...	...	...	...	...	...
		100	41	285	30	205	10	...	...	60	415	42	290	5
		1,000	39	270	28	195	11	...	...	57	395	37	255	5
		10,000	38	260	28	195	10	...	...	55	380	37	255	5
450	230	0.1	35	240	30	205	16	...	...	...	...	...	...	...
		0.5	35	240	29	200	16	...	...	...	...	...	...	...
		100	34	235	23	160	13	...	...	55	380	31	215	7
		1,000	34	235	23	160	12	...	...	54	370	30	205	6
		10,000	34	235	23	160	10	...	...	54	370	30	205	6
500	260	0.1	31	215	25	170	18	...	...	...	...	...	...	...
		0.5	31	215	24	165	18	...	...	...	...	...	...	...
		100	31	215	20	140	13	...	...	54	370	30	205	7
		1,000	31	215	20	140	10	...	...	54	370	29	200	7
		10,000	31	215	20	140	9	...	...	53	365	29	200	6
600	315	0.1	22	150	18	125	20	...	...	...	...	...	...	...
		0.5	22	150	18	125	20	...	...	...	...	...	...	...
		100	23	160	16	110	11	...	...	51	350	28	195	6
		1,000	23	160	15	105	11	...	...	50	345	27	185	6
		5,000	21	145	15	105	11	...	...	47	325	26	180	5
700	370	1,000	6.5	45	6.0	41	46	...	...	...	...	...	...	...

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.3 240.0-F Sand castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4*D*, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4*D*, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
75	25	...	34	235	29	200	1	11.2	77	34	235	29	200	1
212	100	0.5	34	235	29	200	1	...	...	34	235	29	200	1
		10	34	235	29	200	1	...	...	34	235	29	200	1
		100	34	235	29	200	1	...	...	34	235	29	200	1
		1,000	34	235	29	200	1	...	...	34	235	29	200	1
		10,000	34	235	29	200	1	...	...	34	235	29	200	1
300	150	0.5	34	235	29	200	1	...	...	34	235	29	200	1
		10	34	235	29	200	1	...	...	34	235	29	200	1
		100	34	235	29	200	1	...	...	34	235	30	207	1
		1,000	34	235	30	205	1	...	...	34	235	31	215	1
		10,000	34	235	30	205	1	...	...	34	235	31	215	1
400	205	0.5	33	230	27	185	1	...	...	34	235	29	200	1
		10	34	235	30	205	1	...	...	35	240	31	215	1
		100	35	240	29	200	1	...	...	36	250	31	215	1
		1,000	34	235	27	185	1	...	...	36	250	29	200	1
		10,000	33	230	25	170	1	...	...	35	240	27	185	1
500	260	0.5	31	215	24	165	1	...	...	34	235	30	205	1
		10	30	205	20	140	1.5	...	...	34	235	28	195	1
		100	28	195	19	130	2.5	...	...	34	235	26	180	1
		1,000	27	185	18	125	3	...	...	35	240	24	165	1
		10,000	26	180	16	110	4	...	...	35	240	23	160	1
600	315	0.5	21	145	16	110	25	...	...	31	215	26	180	1
		10	21	145	16	110	25	...	...	30	205	25	170	1
		100	20	140	15	105	25	...	...	29	200	23	160	1
		1,000	19	130	13	90	26	...	...	28	195	22	150	1
		10,000	17	115	12	85	40	...	...	28	195	20	140	1
700	370	0.5	13	90	7.5	52	48	...	...	30	205	22	150	1
		10	12	85	7.0	48	50	...	...	29	200	21	145	1
		100	11	75	6.5	45	62	...	...	27	185	20	140	1
		1,000	10	70	6.0	41	66	...	...	26	180	18	125	1
		10,000	9.0	62	5.5	38	70	...	...	25	170	17	115	1

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.4 242.0-T571 Permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4*D*, %	Modulus of elasticity(a)		Tensile strength(b)		Yield strength(b)		Elongation in 4*D*, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
−320	−196	…	44	305	41	285	1	…	…	…	…	…	…	…
−112	−80	…	41	285	36	250	1	…	…	…	…	…	…	…
−18	−28	…	40	275	34	235	1	…	…	…	…	…	…	…
75	25	…	40	275	34	235	1	10.2	70	40	275	34	235	1
212	100	0.5	40	275	34	235	1	…	…	40	275	34	235	1
		10	40	275	34	235	1	…	…	40	275	34	235	1
		100	40	275	34	235	1	…	…	40	275	34	235	1
		1,000	40	275	37	255	1	…	…	40	275	37	255	1
		10,000	42	290	38	260	1	…	…	45	310	40	275	1
300	150	0.5	40	275	33	230	2	…	…	40	275	34	235	2
		10	40	275	34	235	1	…	…	40	275	34	235	2
		100	41	285	36	250	1	…	…	46	315	36	250	2
		1,000	40	275	37	255	1	…	…	44	305	41	285	1
		10,000	38	260	30	205	1	…	…	42	290	38	260	1
350	177	0.5	39	270	31	215	3	…	…	40	275	34	235	2
		10	40	275	34	235	2	…	…	41	285	35	240	2
		100	40	275	36	250	1	…	…	46	315	41	285	1
		1,000	36	250	30	205	2	…	…	41	285	39	270	1
		10,000	33	230	24	165	4	…	…	39	270	30	205	1
400	205	0.5	38	260	29	200	4	…	…	40	275	34	235	2
		10	40	275	35	240	2	…	…	46	315	40	275	2
		100	35	240	28	195	2	…	…	42	290	40	275	1
		1,000	30	205	23	160	6	…	…	38	260	29	200	2
		10,000	27	185	18	125	9	…	…	35	240	22	150	3
450	230	0.5	35	240	26	180	5	…	…	45	310	41	285	1
		10	33	230	27	185	4	…	…	45	310	40	275	2
		100	28	195	21	145	5	…	…	38	260	30	205	2
		1,000	24	165	16	110	10	…	…	34	235	21	145	3
		10,000	20	140	12	85	15	…	…	30	205	16	110	4
500	260	0.5	30	205	23	160	8	…	…	43	295	38	260	1
		10	26	180	19	130	6	…	…	40	275	28	195	2
		100	22	150	15	105	10	…	…	34	235	22	150	2
		1,000	18	125	11	75	15	…	…	30	205	15	105	5
		10,000	15	105	8.0	55	20	…	…	26	180	12	85	6
600	315	0.5	16	110	12	85	25	…	…	34	235	22	150	2
		10	13	90	9.0	62	30	…	…	33	230	14	95	7
		100	12	85	7.5	52	35	…	…	30	205	12	85	7
		1,000	10	70	6.5	45	35	…	…	28	195	11	75	7
		10,000	10	70	6.0	41	35	…	…	26	180	10	70	8
700	370	0.5	8.5	59	6.0	41	65	…	…	…	…	…	…	…
		10	7.5	52	5.5	38	65	…	…	…	…	…	…	…
		100	7.0	48	4.8	33	70	…	…	…	…	…	…	…
		1,000	6.5	45	4.3	30	75	…	…	…	…	…	…	…
		10,000	6.0	41	3.8	26	85	…	…	…	…	…	…	…

(a) The modulus of elasticity in compression is about 2% greater than in tension. (b) Cooled in still air at room temperature; tested within 2 h after removal from furnace. These properties may increase with time after removal from furnace.
Source data are in English units; metric values are converted and rounded.

Table D4.5 242.0-T77 Sand castings: typical tensile properties

Temperature			At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 4*D*, %	10^6 psi	GPa
−320	−196	...	37	255	28	195	2	...	...
−112	−80	...	32	220	24	165	2	...	...
−18	−28	...	31	215	23	160	2	...	...
75	25	...	30	205	23	160	2	10.3	71
212	100	0.5	30	205	23	160	2	...	...
		10	30	205	23	160	2	...	...
		100	30	205	23	160	2	...	...
		1,000	30	205	23	160	2	...	...
		10,000	30	205	23	160	2	...	...
300	150	0.5	29	200	22	150	2	...	...
		10	29	200	22	150	2	...	...
		100	29	200	22	150	2	...	...
		1,000	28	195	22	150	2	...	...
		10,000	27	185	21	145	2	...	...
400	205	0.5	26	180	19	130	2	...	...
		10	24	165	18	125	2	...	...
		100	23	160	17	115	2	...	...
		1,000	22	150	16	110	2	...	...
		10,000	20	140	15	105	3	...	...
500	260	0.5	21	145	16	110	2	...	...
		10	19	130	15	105	2	...	...
		100	17	115	13	90	3	...	...
		1,000	15	105	10	70	4	...	...
		10,000	13	90	8.0	55	6	...	...
600	315	0.5	15	105	11	75	4	...	...
		10	13	90	9.5	66	6	...	...
		100	11	75	7.5	52	8	...	...
		1,000	9.5	66	5.5	38	12	...	...
		10,000	8.0	55	4.0	28	20	...	...
700	370	0.5	9.0	62	6.0	41	8	...	...
		10	7.5	52	5.0	34	20	...	...
		100	6.0	41	4.0	28	30	...	...
		1,000	5.0	34	3.5	24	35	...	...
		10,000	5.0	34	3.0	21	40	...	...

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.6 249.0-T7 Sand and permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4D, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4D, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
−452	−269	…	94	650	76	525	10	…	…	…	…	…	…	…
−423	−253	…	91	627	75	515	9	…	…	…	…	…	…	…
−320	−196	…	81	560	69	475	7	…	…	…	…	…	…	…
−112	−80	…	70	485	62	425	6	…	…	…	…	…	…	…
−18	−28	…	69	475	60	415	6	…	…	…	…	…	…	…
75	25	…	68	470	59	405	6	10.3	71	68	470	59	405	6
300	150	0.5	55	380	52	360	10	…	…	67	460	59	405	6
		10	57	395	52	360	10	…	…	68	470	60	415	5
		100	55	380	50	345	11	…	…	67	460	59	405	5
		1,000	47	325	41	285	14	…	…	63	435	51	350	6
		10,000	42	290	35	240	14	…	…	57	395	42	290	6
350	177	0.5	51	350	48	330	10	…	…	68	470	60	415	7
		10	50	345	46	315	11	…	…	66	455	57	395	5
		100	45	310	41	285	13	…	…	62	425	50	345	6
		1,000	37	255	32	220	14	…	…	57	395	42	290	6
		10,000	34	235	28	195	17	…	…	50	345	35	240	6
400	205	0.5	46	315	41	285	10	…	…	66	455	57	395	6
		10	40	275	36	250	12	…	…	62	425	50	345	6
		100	36	250	32	220	15	…	…	56	385	42	290	7
		1,000	29	200	25	170	16	…	…	50	345	35	240	7
		10,000	27	185	23	160	20	…	…	45	310	30	205	9

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.7 295.0-T6 Sand castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated						
			Tensile strength		Yield strength		Elongation in 4D, %	Modulus of elasticity(a)	
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa
75	25	…	36	250	24	165	5	10	69
212	100	10,000	34	235	23	160	5	…	…
300	150	10,000	28	195	20	140	5	…	…
400	205	10,000	15	105	9.0	62	15	…	…
500	260	10,000	9.0	62	6.0	41	25	…	…
600	315	10,000	4.0	28	3.0	21	75	…	…
700	370	10,000	2.5	17	1.5	10	100	…	…

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.8 319.0-F Sand castings: typical tensile properties

Temperature			At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 2 in. (50 mm), %	10^6 psi	GPa
−320	−196	...	32	220	25	170	2	...	...
−112	−80	...	28	195	20	140	2	...	...
−18	−28	...	27	185	18	125	2	...	...
75	25	...	27	185	18	125	2	10.6	73
212	100	0.5	26	180	17	115	1.5	...	...
		10	26	180	17	115	1.5	...	...
		100	27	185	18	125	1.5	...	...
		1,000	32	220	30	205	1.5	...	...
		10,000	34	235	34	235	1.5	...	...
300	150	0.5	23	160	14	95	1	...	...
		10	26	180	19	130	1	...	...
		100	30	205	30	205	1	...	...
		1,000	30	205	29	200	1	...	...
		10,000	28	195	25	170	1	...	...
350	177	0.5	23	160	16	110	1	...	...
		10	27	185	26	180	1	...	...
		100	28	195	27	185	1	...	...
		1,000	27	185	24	165	1	...	...
		10,000	24	165	20	140	1	...	...
400	205	0.5	24	165	22	150	1	...	...
		10	25	170	23	160	1	...	...
		100	24	165	21	145	1	...	...
		1,000	23	160	18	125	2	...	...
		10,000	20	140	16	110	2	...	...
450	230	0.5	22	150	20	140	1	...	...
		10	22	150	19	130	1.5	...	...
		100	20	140	16	110	1.5	...	...
		1,000	18	125	14	95	2.5	...	...
		10,000	17	115	13	90	3.5	...	...
500	260	0.5	19	130	17	115	1.5	...	...
		10	18	125	15	105	2	...	...
		100	15	105	12	85	2.5	...	...
		1,000	15	105	11	75	3.5	...	...
		10,000	14	95	10	70	4.5	...	...
600	315	0.5	13	90	11	75	3	...	...
		10	11	75	8.5	59	5	...	...
		100	9.5	66	7.5	52	5.5	...	...
		1,000	9.5	66	7.0	48	5.5	...	...
		10,000	9.5	66	6.5	45	5.5	...	...
700	370	0.5	7.0	48	6.0	41	8	...	...
		10	7.0	48	5.5	38	11	...	...
		100	7.0	48	5.5	38	11	...	...
		1,000	7.0	48	5.5	38	11	...	...
		10,000	7.0	48	5.5	38	11	...	...

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.9 319.0-T5 Sand castings: typical tensile properties

Temperature			At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 2 in. (50 mm), %	10^6 psi	GPa
−320	−196	...	35	240	32	220	1	...	...
−112	−80	...	32	220	27	185	1.5	...	...
−18	−28	...	31	215	27	185	1.5	...	...
75	25	...	30	205	26	180	1.5	10.6	73
212	100	0.5	28	195	25	170	1.5	...	...
		10	28	195	25	170	1.5	...	...
		100	28	195	25	170	1.5	...	...
		1,000	29	200	26	180	1.5	...	...
		10,000	31	215	29	200	1.5	...	...
300	150	0.5	26	180	23	160	1	...	...
		10	29	200	26	180	1	...	...
		100	29	200	26	180	1	...	...
		1,000	28	195	25	170	1	...	...
		10,000	27	185	24	165	1	...	...
350	177	0.5	25	170	22	150	1	...	...
		10	28	195	24	165	1	...	...
		100	27	185	23	160	1	...	...
		1,000	26	180	22	150	1	...	...
		10,000	23	160	19	130	1	...	...
400	205	0.5	24	165	22	150	1	...	...
		10	25	170	22	150	1	...	...
		100	24	165	21	145	1	...	...
		1,000	23	160	18	125	2	...	...
		10,000	20	140	16	110	2	...	...
450	230	0.5	22	150	20	140	1	...	...
		10	22	150	19	130	1.5	...	...
		100	20	140	16	110	1.5	...	...
		1,000	18	125	14	95	2.5	...	...
		10,000	17	115	13	90	3.5	...	...
500	260	0.5	19	130	17	115	1.5	...	...
		10	18	125	15	105	2	...	...
		100	15	105	12	85	2.5	...	...
		1,000	15	105	11	75	3.5	...	...
		10,000	14	95	10	70	4.5	...	...
600	315	0.5	13	90	11	75	3	...	...
		10	11	75	8.5	59	5	...	...
		100	9.5	66	7.5	52	5.5	...	...
		1,000	9.5	66	7.0	48	5.5	...	...
		10,000	9.5	66	6.5	45	5.5	...	...
700	370	0.5	7.0	48	6.0	41	8	...	...
		10	7.0	48	5.5	38	11	...	...
		100	7.0	48	5.5	38	11	...	...
		1,000	7.0	48	5.5	38	11	...	...
		10,000	7.0	48	5.5	38	11	...	...

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.10 332.0-T5 Permanent mold castings: typical tensile properties

Temperature			At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 4*D*, %	10^6 psi	GPa
75	24	...	36	250	28	195	1	11.1	77
400	205	100	24	165	17	115	3	...	...
		1,000	21	145	14	95	4	...	...
		10,000	20	140	13	90	5	...	...
450	230	100	20	140	14	95	4	...	...
		1,000	18	125	11	75	5	...	...
		10,000	17	115	10	70	5	...	...
500	260	100	16	110	11	75	6	...	...
		1.000	14	95	8.5	59	7	...	...
		10,000	13	90	7.5	52	8	...	...
600	315	0.5	13	90	9.5	66	10	...	...
		10	12	85	7.5	52	12	...	...
		100	10	70	6.0	41	14	...	...
		1,000	9.0	62	5.0	34	17	...	...
		10,000	7.5	52	5.0	34	25	...	...

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.11 330.0-T5 Permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated					At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4D, %	Tensile strength		Yield strength		Elongation in 4D, %
°F	°C		ksi	MPa	ksi	MPa		ksi	MPa	ksi	MPa	
−320	−196	...	40	275	28	195	1	...	...	...	...	...
−112	−80	...	37	255	26	180	1	...	...	...	...	...
−18	−28	...	35	240	25	170	1	...	...	...	...	...
75	25	...	34	235	25	170	1	34	235	25	170	1
212	100	0.5	34	235	25	170	1	34	235	25	170	1
		10	34	235	25	170	1	34	235	25	170	1
		100	34	235	25	170	1	34	235	25	170	1
		1,000	34	235	25	170	1.5	34	235	25	170	1
		10,000	34	235	25	170	2	34	235	25	170	1
300	150	0.5	34	235	25	170	1	34	235	25	170	1
		10	34	235	25	170	1.5	34	235	25	170	1
		100	33	230	25	170	2	34	235	25	170	1
		1,000	32	220	25	170	2.5	34	235	25	170	1
		10,000	31	215	22	150	3	34	235	25	170	1.5
350	177	0.5	33	230	25	170	1.5	34	235	25	170	1.5
		10	32	220	25	170	2	34	235	25	170	1.5
		100	31	215	25	170	2.5	34	235	25	170	1.5
		1,000	30	205	23	160	3	34	235	24	165	1.5
		10,000	28	195	19	130	3.5	34	235	23	160	2
400	205	0.5	32	220	24	165	2	34	235	25	170	1.5
		10	30	205	24	165	2.5	34	235	25	170	1.5
		100	28	195	22	150	3	34	235	24	165	2
		1,000	26	180	19	130	4	34	235	22	150	2
		10,000	24	165	16	110	5	33	230	20	140	2.5
500	260	0.5	25	170	19	130	4	34	235	24	165	2
		10	23	160	16	110	6	34	235	22	150	2
		100	20	140	12	85	8	33	230	18	125	2
		1,000	18	125	11	75	10	32	220	16	110	3
		10,000	17	115	10	70	11	30	205	15	105	4
600	315	0.5	16	110	11	75	13	33	230	22	150	2
		10	14	95	8.5	59	17	32	220	18	125	3
		100	13	90	7.5	52	20	31	215	16	110	3
		1,000	12	85	7.0	48	25	30	205	15	105	4
		10,000	10	70	7.0	48	30	29	200	14	95	5
700	370	0.5	9.0	62	6.0	41	30	31	215	15	105	3
		10	8.0	55	5.5	38	35	30	205	15	105	4
		100	7.5	52	5.0	34	35	30	205	14	95	5
		1,000	6.5	45	4.8	33	40	30	205	13	90	6
		10,000	6.0	41	4.8	33	45	29	200	13	90	7

Source data are in English units; metric values are converted and rounded.

Table D4.12 330.0-T7 Permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated					At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4D, %	Tensile strength		Yield strength		Elongation, %
°F	°C		ksi	MPa	ksi	MPa		ksi	MPa	ksi	MPa	
−320	−196	...	46	315	32	220	2	...	...	...	...	...
−112	−80	...	41	285	29	200	2	...	...	...	...	...
−18	−28	...	38	260	28	195	2	...	...	...	...	...
75	25	...	37	255	28	195	2	37	255	28	195	2
212	100	0.5	37	255	28	195	4	37	255	28	195	2
		10	37	255	28	195	4	37	255	28	195	2
		100	37	255	28	195	4	37	255	28	195	2
		1,000	36	250	28	195	4	37	255	28	195	2
		10,000	36	250	27	185	4	37	255	28	195	2
300	150	0.5	34	235	25	170	6	37	255	28	195	3
		10	34	235	25	170	6	37	255	28	195	3
		100	34	235	25	170	6	37	255	28	195	3
		1,000	33	230	25	170	6	37	255	28	195	3
		10,000	31	215	24	165	6	37	255	26	180	3
350	177	0.5	32	220	24	165	6	37	255	28	195	3
		10	32	220	24	165	6	37	255	28	195	3
		100	31	215	23	160	7	37	255	28	195	3
		1,000	30	205	22	150	8	37	255	27	185	4
		10,000	26	180	20	140	9	35	240	22	150	4
400	205	0.5	29	200	22	150	7	37	255	28	195	3
		10	29	200	22	150	8	37	255	28	195	4
		100	27	185	21	145	10	37	255	27	185	4
		1,000	25	170	18	125	12	35	240	22	150	5
		10,000	20	140	14	95	14	32	220	18	125	5
500	260	0.5	21	145	17	115	10	37	255	26	180	4
		10	19	130	14	95	15	36	250	21	145	5
		100	14	95	10	70	20	33	230	16	110	6
		1,000	13	90	8.5	59	30	30	205	13	90	7
		10,000	12	85	7.5	52	35	27	185	11	75	7
600	315	0.5	13	90	9.5	66	40	36	250	19	130	5
		10	9.5	66	7.0	48	45	33	230	15	105	6
		100	9.0	62	6.0	41	50	30	205	13	90	7
		1,000	8.0	55	5.5	38	50	28	195	11	75	7
		10,000	8.0	55	5.0	34	55	26	180	10	70	8
700	370	0.5	6.5	45	5.0	34	55	34	235	15	105	7
		10	6.5	45	4.8	33	55	32	220	13	90	7
		100	6.0	41	4.4	30	60	30	205	11	75	7
		1,000	6.0	41	4.1	28	60	28	195	10	70	8
		10,000	5.5	38	3.8	26	60	26	180	10	70	8

Source data are in English units; metric values are converted and rounded.

Table D4.13 336.0-T551 Permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated					At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4D, %	Tensile strength		Yield strength		Elongation in 4D, %
°F	°C		ksi	MPa	ksi	MPa		ksi	MPa	ksi	MPa	
−320	−196	...	44	305	39	270	1	...	...	...	...	...
−112	−80	...	38	260	30	205	0.5	...	...	...	...	...
−18	−28	...	37	255	28	195	0.5	...	...	...	...	...
75	25	...	36	250	28	195	0.5	...	...	...	...	...
212	100	0.5	36	250	28	195	0.5	36	250	28	195	0.5
		10	36	250	28	195	0.5	36	250	28	195	0.5
		100	36	250	28	195	0.5	36	250	28	195	0.5
		1,000	36	250	28	195	0.5	36	250	28	195	0.5
		10,000	35	240	27	185	0.5	36	250	28	195	0.5
300	150	0.5	34	235	26	180	0.5	36	250	28	195	0.5
		10	34	235	26	180	0.5	36	250	28	195	0.5
		100	34	235	25	170	0.5	36	250	28	195	0.5
		1,000	33	230	24	165	0.5	36	250	27	185	0.5
		10,000	32	220	23	160	0.5	36	250	24	165	0.5
350	177	0.5	32	220	24	165	0.5	36	250	28	195	0.5
		10	32	220	23	160	0.5	36	250	27	185	0.5
		100	31	215	22	150	0.5	36	250	26	180	0.5
		1,000	30	205	21	145	0.5	36	250	23	160	0.5
		10,000	28	195	19	130	1	35	240	20	140	0.5
400	205	0.5	30	205	20	140	1	36	250	28	195	0.5
		10	29	200	19	130	1	36	250	26	180	0.5
		100	29	200	18	125	1	36	250	24	165	0.5
		1,000	27	185	17	115	1	36	250	21	145	0.5
		10,000	25	170	15	105	2	33	230	18	125	0.8
450	230	0.5	27	185	17	115	1	36	250	27	185	0.5
		10	26	180	16	110	1	36	250	25	170	0.5
		100	25	170	15	105	1.5	35	240	23	160	0.5
		1,000	24	165	14	95	2	35	240	20	140	0.5
		10,000	22	150	12	85	4	31	215	18	125	1.3
500	260	0.5	23	160	14	95	2	36	250	26	180	0.5
		10	22	150	13	90	2	36	250	24	165	0.5
		100	21	145	12	85	3	34	235	22	150	0.5
		1,000	20	140	11	75	3.5	33	230	20	140	0.7
		10,000	18	125	10	70	5	31	215	18	125	2
600	315	0.5	14	95	8.0	55	10	36	250	24	165	0.7
		10	13	90	7.5	52	10	35	240	22	150	0.7
		100	12	85	7.0	48	11	33	230	20	140	0.9
		1,000	12	85	6.5	45	12	31	215	18	124	2
		10,000	11	75	6.0	41	15	...	...	...	...	...
700	370	0.5	8.5	59	4.8	33	27	36	250	22	150	1.5
		10	8.0	55	4.5	31	33	35	240	20	140	1.5
		100	7.5	52	4.3	30	38	31	215	18	125	2
		1,000	7.0	48	4.2	29	41	...	...	...	...	...
		10,000	7.0	48	4.0	28	43	...	...	...	...	...

Source data are in English units; metric values are converted and rounded.

Table D4.14 A344.0-T4 Permanent mold castings (results of tests on permanent mold test bars): typical tensile properties

Temperature		At temperature indicated				
		Tensile strength		Yield strength		
°F	°C	ksi	MPa	ksi	MPa	Elongation in 4D, %
75	25	22	150	8.0	55	30

Source data are in English units; metric values are converted and rounded.

Table D4.15 354.0-T6, -T61 Permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4D, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4D, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
−320	−196	...	68	470	49	340	5	...	...	...	...	...	...	...
−112	−80	...	58	400	42	290	5	...	...	...	...	...	...	...
−18	−28	...	58	400	42	290	5	...	...	...	...	...	...	...
75	25	...	55	380	41	285	6	10.6	73	55	380	41	285	6
212	100	0.5	50	345	41	285	6	...	...	55	380	41	285	6
		10	51	350	41	285	6	...	...	56	385	42	290	6
		100	52	360	42	290	6	...	...	58	400	43	295	6
		1,000	54	370	45	310	6	...	...	61	420	45	310	6
		10,000	60	415	49	340	6	...	...	63	435	51	350	5
300	150	0.5	47	325	40	275	6	...	...	55	380	42	290	6
		10	50	345	43	295	6	...	...	57	395	44	305	5
		100	51	350	46	315	6	...	...	62	425	50	345	5
		1,000	49	340	44	305	6	...	...	59	405	52	360	4
		10,000	42	290	35	240	6	...	...	49	340	40	275	6
350	177	0.5	45	310	39	270	6	...	...	55	380	43	295	6
		10	47	325	42	290	6	...	...	59	405	49	340	4
		100	43	295	38	260	8	...	...	59	405	51	350	5
		1,000	33	230	28	195	13	...	...	47	325	37	255	8
		10,000	19	130	14	95	24	...	...	30	205	17	115	16
400	205	0.5	42	290	39	270	6	...	...	59	405	49	340	5
		10	39	270	36	250	9	...	...	58	400	49	340	5
		100	30	205	26	180	17	...	...	48	330	37	255	7
		1,000	19	130	15	105	30	...	...	32	220	18	125	14
		10,000	15	105	11	75	45	...	...	27	185	13	90	20
450	230	0.5	37	255	35	240	9	...	...	58	400	50	345	5
		10	28	195	25	170	15	...	...	46	315	36	250	8
		100	18	125	14	95	25	...	...	35	240	20	140	11
		1,000	14	95	11	75	40	...	...	28	195	14	95	17
		10,000	12	85	8.5	59	55	...	...	25	170	11	75	22
500	260	0.5	28	195	25	170	16	...	...	52	360	42	290	6
		10	17	115	15	105	22	...	...	36	250	22	150	11
		100	12	85	9.5	66	35	...	...	30	205	15	105	15
		1,000	9.5	66	7.5	52	50	...	...	27	185	12	85	19
		10,000	8.5	59	6.0	41	65	...	...	24	165	10	70	22
600	315	0.5	13	90	12	85	29	...	...	38	260	21	145	13
		10	8.5	59	7.0	48	60	...	...	30	205	13	90	17
		100	6.0	41	5.0	34	85	...	...	27	185	11	75	19
		1,000	...	...	...	...	...	...	...	25	170	9.5	66	21
		10,000	...	...	...	...	...	...	...	23	160	8.5	59	23

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.16 355.0-T51 Sand castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C		ksi	MPa	ksi	MPa	Elongation in 4D, %	10^6 psi	GPa
−320	−196	...	33	230	27	185	1.5	...	...
−112	−80	...	29	200	24	165	1.5	...	...
−18	−28	...	28	195	23	160	1.5	...	...
75	25	...	28	195	23	160	1.5	10.2	70
212	100	0.5	28	195	22	150	1.5	...	...
		10	28	195	22	150	2	...	...
		100	28	195	22	150	2	...	...
		1,000	28	195	22	150	2	...	...
		10,000	28	195	22	150	2	...	...
300	150	0.5	26	180	21	145	2	...	...
		10	26	180	21	145	2	...	...
		100	26	180	20	140	2	...	...
		1,000	25	170	20	140	2	...	...
		10,000	24	165	19	130	3	...	...
400	205	0.5	22	150	18	125	3	...	...
		10	22	150	17	115	3	...	...
		100	20	140	16	110	3	...	...
		1,000	17	115	14	95	5	...	...
		10,000	14	95	10	70	8	...	...
500	260	0.5	15	105	14	95	5	...	...
		10	14	95	12	85	7	...	...
		100	12	85	10	70	10	...	...
		1,000	10	70	7.5	52	13	...	...
		10,000	9.5	66	5.0	34	16	...	...
600	315	0.5	9.5	66	8.5	59	13	...	...
		10	8.0	55	7.0	48	19	...	...
		100	7.0	48	5.0	34	24	...	...
		1,000	6.0	41	4.0	28	30	...	...
		10,000	6.0	41	3.0	21	36	...	...
700	370	0.5	5.5	38	4.5	31	25	...	...
		10	5.0	34	3.5	24	30	...	...
		100	4.5	31	3.0	21	40	...	...
		1,000	3.5	24	2.0	14	45	...	...
		10,000	3.5	24	2.0	14	50	...	...

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.17 355.0-T6 Sand castings: typical tensile properties

Temperature			At temperature indicated				
			Tensile strength		Yield strength		
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 4*D*, %
75	25	…	35	240	25	170	3
212	100	0.5	35	240	25	170	3
		10	35	240	25	170	3
		100	36	250	26	180	3
		1,000	37	255	30	205	3
		10,000	40	275	35	240	3
300	150	0.5	34	235	25	170	3
		10	37	255	30	205	3
		100	39	270	34	235	3
		1,000	39	270	36	250	3
		10,000	33	230	29	200	3
350	177	0.5	34	235	25	170	3
		10	38	260	33	230	3
		100	37	255	34	235	3
		1,000	30	205	28	195	3
		10,000	23	160	18	125	5
400	205	0.5	33	230	25	170	3
		10	35	240	30	205	3
		100	30	205	26	180	3
		1,000	20	140	17	115	5
		10,000	15	105	11	75	6
500	260	0.5	22	150	19	130	5
		10	17	115	15	105	6
		100	14	95	11	75	8
		1,000	11	75	9.0	62	13
		10,000	9.5	66	6.0	41	16
600	315	0.5	10	70	9.0	62	10
		10	8.5	59	7.0	48	15
		100	7.5	52	6.0	41	22
		1,000	6.5	45	4.5	31	30
		10,000	6.0	41	3.0	21	36
700	370	0.5	5.5	38	4.5	31	25
		10	5.0	34	3.5	24	30
		100	4.5	31	3.0	21	40
		1,000	4.0	28	2.5	17	45
		10,000	3.5	24	2.0	14	50

Source data are in English units; metric values are converted and rounded.

Table D4.18 355.0-T6 Sand castings: cryogenic tensile properties (not typical)

Temperature		Tensile yield strength		Tensile ultimate strength		Elongation,	Reduction in
°F	°C	ksi	MPa	ksi	MPa	%	area, %
–423	–253	57.2	394	63.6	439	2.5	2.5
–423	–253	56.3	388	63.5	438	1.0	1.0
–320	–196	48.0	331	61.2	422	2.0	4.0
–320	–196	45.0	310	57.3	395	2.0	4.0
–104	–76	41.2	284	52.0	359	4.0	7.0
–104	–76	28.6	197	37.4	258	5.0	6.0
78	26	24.0	165	32.8	226	4.0	4.0
78	26	28.6	197	32.6	225	4.0	3.0

Source data are in English units; metric values are converted and rounded.
Source: Ref 2

Table D4.19 355.0-T62 Permanent mold castings: typical tensile properties

Temperature		Modulus of elasticity(a)	
°F	°C	10^6 psi	GPa
75	25	10.2	70

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.20 355.0-T71 Permanent mold castings: typical tensile properties

Temperature		Modulus of elasticity(a)	
°F	°C	10^6 psi	GPa
75	25	10.2	70

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.21 355.0-T71 Sand castings: typical tensile properties

Temperature			At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 4*D*, %	10^6 psi	GPa
75	25	...	35	240	29	200	1.5	10.2	70
212	100	0.5	34	235	28	195	1.5	...	...
		10	34	235	28	195	2	...	...
		100	34	235	28	195	2	...	...
		1,000	34	235	28	195	2	...	...
		10,000	34	235	28	195	2	...	...
300	150	0.5	30	205	26	180	2	...	...
		10	30	205	26	180	2	...	...
		100	30	205	26	180	2	...	...
		1,000	30	205	26	180	2	...	...
		10,000	30	205	26	180	3	...	...
400	205	0.5	26	180	23	160	3	...	...
		10	26	180	23	160	3	...	...
		100	25	170	21	145	3	...	...
		1,000	20.	140	16	110	5	...	...
		10,000	17	115	13	90	8	...	...
500	260	0.5	20	140	18	125	5	...	...
		10	17	115	15	105	6	...	...
		100	14	95	11	75	8	...	...
		1,000	11	75	8.0	55	13	...	...
		10,000	9.5	66	5.0	34	16	...	...
600	315	0.5	12	85	10	70	10	...	...
		10	9.5	66	8.0	55	15	...	...
		100	7.0	48	5.5	38	22	...	...
		1,000	6.0	41	4.0	28	30	...	...
		10,000	6.0	41	3.0	21	36	...	...
700	370	0.5	5.5	38	4.5	31	25	...	...
		10	5.0	34	3.5	24	30	...	...
		100	4.5	31	3.0	21	40	...	...
		1,000	3.5	24	2.0	14	45	...	...
		10,000	3.5	24	2.0	14	50	...	...

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.22 A355.0-T51 Sand castings: typical tensile properties

Temperature			At temperature indicated				
			Tensile strength		Yield strength		
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in in 4*D*, %
75	25	...	28	195	24	165	1.5
212	100	0.5	28	195	23	160	1.5
		10	28	195	23	160	1.5
		100	28	195	23	160	1.5
		1,000	27	185	23	160	1.5
		10,000	27	185	23	160	1.5
300	150	0.5	26	180	21	145	1.5
		10	25	170	21	145	1.5
		100	25	170	20	140	1.5
		1,000	24	165	20	140	1.5
		10,000	24	165	20	140	2
400	205	0.5	22	150	18	125	2
		10	21	145	16	110	2
		100	19	130	15	105	3
		1,000	18	125	13	90	3
		10,000	17	115	12	85	4
500	260	0.5	17	115	14	95	4
		10	15	105	11	75	5
		100	13	90	9.5	66	6
		1,000	12	85	8.0	55	8
		10,000	11	75	7.0	48	10
600	315	0.5	12	85	8.5	59	9
		10	10	70	7.0	48	9
		100	9.0	62	6.0	41	9
		1,000	8.5	59	5.5	38	9
		10,000	7.5	52	5.0	34	10
700	370	0.5	7.0	48	5.0	34	10
		10	7.0	48	4.5	31	10
		100	6.5	45	4.5	31	10
		1,000	6.0	41	4.0	28	12
		10,000	6.0	41	4.0	28	15

Source data are in English units; metric values are converted and rounded.

Table D4.23 C355.0-T6 Sand and permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4*D*, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4*D*, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
−320	−196	...	56	385	37	255	7	...	...	...	...	...	...	...
−112	−80	...	50	345	34	235	7	...	...	...	...	...	...	...
−18	−28	...	48	330	34	235	7	...	...	...	...	...	...	...
75	25	...	46	315	34	235	6	10.1	70	46	315	34	235	6
212	100	0.5	44	305	32	220	6	...	...	46	315	34	235	6
		10	44	305	33	230	6	...	...	46	315	34	235	6
		100	44	305	35	240	6	...	...	48	330	35	240	6
		1,000	45	310	36	250	6	...	...	50	345	38	260	6
		10,000	46	315	40	275	7	...	...	50	345	42	290	5
300	150	0.5	42	290	32	220	10	...	...	46	315	35	240	6
		10	42	290	34	235	10	...	...	49	340	39	270	5
		100	43	295	38	260	10	...	...	50	345	42	290	4
		1,000	42	290	37	255	11	...	...	48	330	45	310	3
		10,000	37	255	32	220	12	...	...	45	310	37	255	6
350	177	0.5	40	275	33	230	11	...	...	48	330	38	260	5
		10	40	275	35	240	13	...	...	49	340	43	295	4
		100	39	270	34	235	15	...	...	47	325	43	295	3
		1,000	31	215	24	165	20	...	...	41	285	33	230	7
		10,000	22	150	15	105	25	...	...	33	230	19	130	12
400	205	0.5	37	255	34	235	13	...	...	49	340	41	285	4
		10	35	240	32	220	15	...	...	46	315	41	285	4
		100	27	185	24	165	20	...	...	42	290	33	230	8
		1,000	16	110	13	90	30	...	...	30	205	18	125	12
		10,000	13	90	9.0	62	40	...	...	24	165	11	75	18
450	230	0.5	31	215	30	205	14	...	...	48	330	40	275	4
		10	25	170	23	160	17	...	...	41	285	32	220	7
		100	17	115	15	105	25	...	...	32	220	21	145	13
		1,000	11	75	8.5	59	40	...	...	25	170	12	85	16
		10,000	9.0	62	6.5	45	50	...	...	23	160	9.0	62	19
500	260	0.5	25	170	24	165	15	...	...	44	305	35	240	6
		10	17	115	15	105	20	...	...	35	241	23	160	10
		100	11	75	10	70	30	...	...	27	185	14	95	15
		1,000	8.5	59	6.5	45	50	...	...	24	165	10	70	18
		10,000	7.0	48	5.0	34	60	...	...	22	150	8.0	55	20
600	315	0.5	13	90	12	83	20	...	...	35	240	20	140	10
		10	8.5	59	6.5	45	35	...	...	29	200	13	90	12
		100	6.0	41	5.0	34	50	...	...	25	170	9.0	62	15
		1,000	5.0	34	3.5	24	65	...	...	23	160	7.5	52	20
		10,000	4.5	31	3.0	21	70	...	...	21	145	6.5	45	30
700	370	0.5	5.5	38	4.5	31	45	...	...	...	...	...	...	...
		10	4.0	28	3.5	24	70	...	...	...	...	...	...	...
		100	3.5	24	3.0	21	90	...	...	...	...	...	...	...
		1,000	3.5	24	2.5	17	95	...	...	...	...	...	...	...
		10,000	3.5	24	2.5	17	95	...	...	...	...	...	...	...

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.24 356.0-T51 Sand castings: typical tensile properties

Temperature			At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength			Modulus of elasticity(a)		Tensile strength		Yield strength		
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 4D, %	10^6 psi	GPa	ksi	MPa	ksi	MPa	Elongation in 4D, %
−320	−196	...	31	215	22	150	2	...	...	...	...	...	...	...
−112	−80	...	26	180	20	140	2	...	...	...	...	...	...	...
−18	−28	...	26	180	20	140	2	...	...	...	...	...	...	...
75	25	...	25	170	20	140	2	10.5	72	25	170	20	140	2
212	100	0.5	24	165	20	140	2	10.3	71	25	170	20	140	2
		10	24	165	20	140	2	10.3	71	25	170	20	140	2
		100	24	165	20	140	2	10.3	71	25	170	20	140	2
		1,000	24	165	20	140	2	10.3	71	25	170	20	140	2
		10,000	24	165	20	140	2	10.3	71	25	170	20	140	2
300	150	0.5	22	150	18	125	2	10.0	69	25	170	20	140	2
		10	22	150	18	125	2	10.0	69	25	170	20	140	2
		100	22	150	18	125	2	10.0	69	25	170	20	140	2
		1,000	22	150	18	125	3	10.0	69	25	170	20	140	2
		10,000	21	145	18	125	4	10.0	69	25	170	18	125	3
400	205	0.5	20	140	16	110	3	9.4	65	25	170	20	140	2
		10	19	130	16	110	4	9.4	65	25	170	20	140	2
		100	18	125	14	95	5	9.4	65	25	170	18	125	3
		1,000	14	95	11	75	6	9.4	65	22	150	14	95	4
		10,000	12	85	8.5	59	8	9.4	65	22	150	11	75	4
500	260	0.5	15	105	13	90	6	8.4	58	25	170	20	140	2
		10	11	75	9.0	62	8	8.4	58	23	160	14	95	3
		100	9.0	62	7.0	48	10	8.4	58	20	140	9.5	66	4
		1,000	8.0	55	6.0	41	12	8.4	58	18	125	9.0	62	5
		10,000	7.5	52	5.0	34	15	8.4	58	17	115	8.5	59	6
600	315	0.5	7.5	52	6.5	45	12	6.8	47	25	170	18	125	2
		10	6.5	45	5.0	34	15	6.8	47	20	140	10	70	4
		100	5.5	38	4.0	28	18	6.8	47	19	130	8.5	59	6
		1,000	5.0	34	3.5	24	24	6.8	47	18	125	8.0	55	8
		10,000	4.0	28	3.0	21	30	6.8	47	17	115	7.5	52	9
700	370	0.5	5.0	34	4.0	28	25	4.2	29	20	140	10	70	4
		10	4.0	28	3.0	21	30	4.2	29	19	130	9.0	62	6
		100	3.0	21	2.5	17	35	4.2	29	18	125	8.0	55	8
		1,000	2.5	17	2.0	14	42	4.2	29	17	115	7.0	48	9
		10,000	2.5	17	2.0	14	50	4.2	29	16	110	7.0	48	10

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.25 356.0-T6 Permanent mold castings: typical tensile properties

Temperature			At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 4*D*, %	10^6 psi	GPa
−423	−253	...	61	420	36	250	3	...	...
−320	−196	...	47	325	32	220	3	...	...
−112	−80	...	43	295	30	205	4	...	...
−18	−28	...	41	285	28	195	4	...	...
75	25	...	38	260	27	185	5	10.4	72
212	100	0.5	34	235	27	185	6	10.2	70
		10	36	250	27	185	6	10.2	70
		100	36	250	27	185	6	10.2	70
		1,000	33	230	26	180	6	10.2	70
		10,000	30	205	25	170	6	10.2	70
300	150	0.5	29	200	25	170	7	9.9	68
		10	32	220	26	180	7	9.9	68
		100	29	200	25	170	8	9.9	68
		1,000	23	160	21	145	9	9.9	68
		10,000	21	145	17	115	10	9.9	68
350	177	0.5	26	180	23	160	8	9.7	67
		10	27	185	24	165	10	9.7	67
		100	23	160	20	140	13	9.7	67
		1,000	18	125	15	105	15	9.7	67
		10,000	16	110	12	85	17	9.7	67
400	205	0.5	23	160	20	140	9	9.4	65
		10	21	145	19	130	15	9.4	65
		100	16	110	13	90	20	9.4	65
		1,000	13	90	9.5	66	25	9.4	65
		10,000	12	85	8.5	59	30	9.4	65
450	230	0.5	19	130	17	115	11	8.9	61
		10	16	110	13	90	21	8.9	61
		100	12	85	9.0	62	29	8.9	61
		1,000	10	70	7.5	52	35	8.9	61
		10,000	9.5	66	6.5	45	45	8.9	61
500	260	0.5	15	105	13	90	17	8.3	57
		10	11	75	9.0	62	28	8.3	57
		100	9.0	62	7.0	48	38	8.3	57
		1,000	8.0	55	6.0	41	46	8.3	57
		10,000	7.5	52	5.0	34	55	8.3	57
600	315	0.5	7.5	52	6.5	45	40	6.8	47
		10	6.5	45	5.0	34	45	6.8	47
		100	5.5	38	4.0	28	50	6.8	47
		1,000	5.0	34	3.5	24	60	6.8	47
		10,000	4.0	28	3.0	21	70	6.8	47
700	370	0.5	5.0	34	4.0	28	60	4.2	29
		10	4.0	28	3.0	21	64	4.2	29
		100	3.0	21	2.5	17	68	4.2	29
		1,000	2.5	17	2.0	14	72	4.2	29
		10,000	2.5	17	2.0	14	80	4.2	29

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.26 356.0-T6 Sand castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4*D*, %	Modulus of elasticity (a)		Tensile strength		Yield strength		Elongation in 4*D*, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
−320	−196	...	40	275	28	195	3.5	...	...	...	...	...	...	...
−112	−80	...	35	240	25	170	3.5	...	...	...	...	...	...	...
−18	−28	...	33	230	24	165	3.5	...	...	...	...	...	...	...
75	25	...	33	230	24	165	3.5	10.4	72	33	230	24	165	3.5
212	100	0.5	32	220	24	165	4	10.2	70	(b)	(b)	(b)	(b)	...
		10	33	230	25	170	4	10.2	70	(b)	(b)	(b)	(b)	...
		100	33	230	26	180	4	10.2	70	(b)	(b)	(b)	(b)	...
		1,000	33	230	27	185	4	10.2	70	(b)	(b)	(b)	(b)	...
		10,000	33	230	25	170	4	10.2	70	(b)	(b)	(b)	(b)	...
300	150	0.5	30	205	24	165	4	9.9	68	(b)	(b)	(b)	(b)	...
		10	32	220	27	185	4	9.9	68	(b)	(b)	(b)	(b)	...
		100	32	220	27	185	4	9.9	68	(b)	(b)	(b)	(b)	...
		1,000	29	200	25	170	5	9.9	68	(b)	(b)	(b)	(b)	...
		10,000	23	160	20	140	6	9.9	68	30	205	23	160	4
350	177	0.5	28	195	24	165	4	9.7	67	(b)	(b)	(b)	(b)	...
		10	29	200	26	180	5	9.7	67	(b)	(b)	(b)	(b)	...
		100	26	180	23	160	6	9.7	67	(b)	(b)	(b)	(b)	...
		1,000	21	145	18	125	8	9.7	67	28	195	21	145	5
		10,000	17	115	13	90	11	9.7	67	24	165	16	110	8
400	205	0.5	26	180	22	150	5	9.4	65	(b)	(b)	(b)	(b)	...
		10	23	160	20	140	6	9.4	65	32	220	26	180	2
		100	18	125	15	105	8	9.4	65	28	195	21	145	4
		1,000	14	95	11	75	13	9.4	65	22	150	14	95	8
		10,000	12	85	8.5	59	18	9.4	65	20	140	11	75	12
450	230	0.5	21	145	19	130	6	8.9	61	(b)	(b)	(b)	(b)	...
		10	16	110	14	95	8	8.9	61	28	195	20	140	3
		100	12	85	9.0	62	12	8.9	61	22	150	14	95	7
		1,000	10	70	7.5	52	19	8.9	61	19	130	10	70	11
		10,000	9.5	66	6.5	45	26	8.9	61	18	125	9.0	62	14
500	260	0.5	15	105	13	90	8	8.3	57	32	220	27	186	3
		10	11	75	9.0	62	12	8.3	57	23	160	14	95	6
		100	9.0	62	7.0	48	18	8.3	57	20	140	9.5	66	10
		1,000	8.0	55	6.0	41	25	8.3	57	18	125	9.0	62	13
		10,000	7.5	52	5.0	34	35	8.3	57	17	115	8.5	59	15
600	315	0.5	7.5	52	6.5	45	20	6.8	47	29	200	22	150	5
		10	6.5	45	5.0	34	24	6.8	47	20	140	10	70	8
		100	5.5	38	4.0	28	33	6.8	47	19	130	8.5	59	12
		1,000	5.0	34	3.5	24	45	6.8	47	18	125	8.0	55	15
		10,000	4.0	28	3.0	21	60	6.8	47	17	115	7.5	52	16
700	370	0.5	5.0	34	4.0	28	35	4.2	29	20	140	10	70	10
		10	4.0	28	3.0	21	46	4.2	29	19	130	9.0	62	13
		100	3.0	21	2.5	17	58	4.2	29	18	125	8.0	55	15
		1,000	2.5	17	2.0	14	68	4.2	29	17	115	7.0	48	16
		10,000	2.5	17	2.0	14	80	4.2	29	16	110	7.0	48	17

(a) The modulus of elasticity in compression is about 2% greater than in tension. (b) Strengths are as high as, or higher than, the original room-temperature strengths. Source data are in English units; metric values are converted and rounded.

Table D4.27 356.0-T7 Permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4*D*, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4*D*, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
−320	−196	...	40	275	30	205	6	...	...	...	...	...	...	...
−112	−80	...	35	240	26	180	6	...	...	...	...	...	...	...
−18	−28	...	34	235	25	170	6	...	...	...	...	...	...	...
75	25	...	32	220	24	165	6	10.5	72	32	220	24	165	6
212	100	0.5	27	185	23	160	8	10.3	71	32	220	24	165	6
		10	27	185	23	160	8	10.3	71	32	220	24	165	6
		100	27	185	23	160	8	10.3	71	32	220	24	165	6
		1,000	27	185	23	160	9	10.3	71	32	220	24	165	7
		10,000	27	185	23	160	10	10.3	71	32	220	24	165	8
300	150	0.5	24	165	22	150	10	10.0	69	31	215	24	165	7
		10	24	165	22	150	12	10.0	69	31	215	24	165	8
		100	24	165	22	150	14	10.0	69	31	215	24	165	9
		1,000	23	160	21	145	17	10.0	69	31	215	24	165	10
		10,000	21	145	17	115	20	10.0	69	27	185	18	125	12
350	177	0.5	22	150	20	140	11	...	...	31	215	24	165	8
		10	22	150	20	140	17	...	...	31	215	24	165	11
		100	21	145	19	130	22	...	...	31	215	23	160	13
		1,000	18	125	15	105	26	...	...	27	185	18	125	16
		10,000	16	110	12	85	31	...	...	22	150	13	90	20
400	205	0.5	21	145	19	130	12	9.4	65	30	205	23	160	10
		10	19	130	17	115	21	9.4	65	30	205	22	150	14
		100	15	105	13	90	28	9.4	65	26	180	18	125	19
		1,000	13	90	9.5	66	34	9.4	65	22	150	12	85	25
		10,000	12	85	8.5	59	40	9.4	65	20	140	11	75	30
500	260	0.5	15	105	13	90	20	8.4	58	29	200	20	140	15
		10	11	75	9.0	62	28	8.4	58	22	150	12	85	20
		100	9.0	62	7.0	48	38	8.4	58	20	140	9.5	66	25
		1,000	8.0	55	6.0	41	46	8.4	58	18	125	9.0	62	30
		10,000	7.5	52	5.0	34	55	8.4	58	17	115	8.5	59	34
600	315	0.5	7.5	52	6.5	45	40	6.8	47	22	150	12	85	20
		10	6.5	45	5.0	34	45	6.8	47	20	140	10	70	25
		100	5.5	38	4.0	28	50	6.8	47	19	130	8.5	59	30
		1,000	5.0	34	3.5	24	60	6.8	47	18	125	8.0	55	33
		10,000	4.0	28	3.0	21	70	6.8	47	17	115	7.5	52	35
700	370	0.5	5.0	34	4.0	28	60	4.2	29	20	140	10	70	25
		10	4.0	28	3.0	21	64	4.2	29	19	130	9.0	62	28
		100	3.0	21	2.5	17	68	4.2	29	18	125	8.0	55	32
		1,000	2.5	17	2.0	14	72	4.2	29	17	115	7.0	48	34
		10,000	2.5	17	2.0	14	80	4.2	29	16	110	7.0	48	35

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.28 356.0-T7 Sand castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4*D*, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4*D*, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
−320	−196	...	41	285	35	240	2	...	...	...	...	...	...	...
−112	−80	...	36	250	32	220	2	...	...	...	...	...	...	...
−18	−28	...	34	235	31	215	2	...	...	...	...	...	...	...
75	25	...	34	235	30	205	2	10.5	72	34	235	30	205	2
212	100	0.5	30	205	28	195	2	10.3	71	34	235	30	205	2
		10	30	205	28	195	2	10.3	71	34	235	30	205	2
		100	30	205	28	195	2	10.3	71	34	235	30	205	2
		1,000	30	205	28	195	2	10.3	71	34	235	30	205	2
		10,000	30	205	28	195	2	10.3	71	34	235	30	205	2
300	150	0.5	26	180	25	170	2	10.0	69	33	230	30	205	2
		10	26	180	25	170	2	10.0	69	33	230	30	205	2
		100	26	180	25	170	2	10.0	69	33	230	30	205	2
		1,000	26	180	24	165	3	10.0	69	33	230	28	195	3
		10,000	23	160	20	140	6	10.0	69	30	205	23	160	4
350	177	0.5	24	165	23	160	2	...	...	33	230	30	205	2
		10	24	165	23	160	3	...	...	33	230	30	205	2
		100	23	160	20	140	4	...	...	33	230	28	195	2
		1,000	20	140	17	115	8	...	...	28	195	21	145	5
		10,000	17	115	13	90	11	...	...	24	165	16	110	8
400	205	0.5	22	150	20	140	3	9.4	65	33	230	29	200	2
		10	21	145	20	140	5	9.4	65	32	220	26	180	2
		100	18	125	15	105	8	9.4	65	28	195	21	145	4
		1,000	14	95	11	75	13	9.4	65	22	150	14	95	8
		10,000	12	85	8.5	59	18	9.4	65	20	140	11	75	12
500	260	0.5	15	105	13	90	8	8.4	58	32	220	27	185	3
		10	11	75	9.0	62	12	8.4	58	23	160	14	95	6
		100	9.0	62	7.0	48	18	8.4	58	20	140	9.5	66	10
		1,000	8.0	55	6.0	41	25	8.4	58	18	125	9.0	62	13
		10,000	7.5	52	5.0	34	35	8.4	58	17	115	8.5	59	15
600	315	0.5	7.5	52	6.5	45	20	6.8	47	29	200	22	150	5
		10	6.5	45	5.0	34	24	6.8	47	20	140	10	70	8
		100	5.5	38	4.0	28	33	6.8	47	19	130	8.5	59	12
		1,000	5.0	34	3.5	24	45	6.8	47	18	125	8.0	55	15
		10,000	4.0	28	3.0	21	60	6.8	47	17	115	7.5	52	16
700	370	0.5	5.0	34	4.0	28	35	4.2	29	20	140	10	70	10
		10	4.0	28	3.0	21	46	4.2	29	19	130	9.0	62	13
		100	3.0	21	2.5	17	58	4.2	29	18	125	8.0	55	15
		1,000	2.5	17	2.0	14	68	4.2	29	17	115	7.0	48	16
		10,000	2.5	17	2.0	14	80	4.2	29	16	110	7.0	48	17

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.29 A356.0-T6, -T61 Permanent mold castings: typical tensile properties

Temperature			At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 4*D*, %	10^6 psi	GPa
−452	−269	...	63	435	48	330	8	...	...
−423	−253	...	61	420	45	310	8	...	...
−320	−196	...	54	370	36	250	10	...	...
−112	−80	...	46	315	32	220	10	...	...
−18	−28	...	43	295	31	215	10	...	...
75	25	...	41	285	30	205	10	10.4	72
212	100	0.5	37	255	28	195	16	10.2	70
		10	37	255	28	195	16	10.2	70
		100	37	255	29	200	14	10.2	70
		1,000	38	260	31	215	13	10.2	70
		10,000	38	260	33	230	12	10.2	70
300	150	0.5	34	235	27	185	19	9.9	68
		10	35	240	28	195	17	9.9	68
		100	36	250	31	215	15	9.9	68
		1,000	32	220	28	195	17	9.9	68
		10,000	21	145	17	115	20	9.9	68
350	177	0.5	32	220	27	185	17	9.7	67
		10	32	220	28	195	16	9.7	67
		100	26	180	24	165	21	9.7	67
		1,000	18	125	15	105	26	9.7	67
		10,000	16	110	12	85	30	9.7	67
400	205	0.5	28	195	26	180	15	9.4	65
		10	25	170	24	165	18	9.4	65
		100	16	110	13	90	27	9.4	65
		1,000	13	90	9.5	66	34	9.4	65
		10,000	12	85	8.5	59	40	9.4	65
450	230	0.5	23	160	22	150	17	8.9	61
		10	17	115	16	110	22	8.9	61
		100	12	85	9.0	62	30	8.9	61
		1,000	10	70	7.5	52	40	8.9	61
		10,000	9.5	66	6.5	45	50	8.9	61
500	260	0.5	16	110	15	105	21	8.3	57
		10	11	75	9.0	62	28	8.3	57
		100	9.0	62	7.0	48	38	8.3	57
		1,000	8.0	55	6.0	41	46	8.3	57
		10,000	7.5	52	5.0	34	55	8.3	57
600	315	0.5	7.5	52	6.5	45	40	6.8	47
		10	6.5	45	5.0	34	45	6.8	47
		100	5.5	38	4.0	28	50	6.8	47
		1,000	5.0	34	3.5	24	60	6.8	47
		10,000	4.0	28	3.0	21	70	6.8	47
700	370	0.5	5.0	34	4.0	28	60	4.2	29
		10	4.0	28	3.0	21	64	4.2	29
		100	3.0	21	2.5	17	68	4.2	29
		1,000	2.5	17	2.0	14	72	4.2	29
		10,000	2.5	17	2.0	14	80	4.2	29

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.30 A357.0-T6, -T61, -T62 Permanent mold castings: typical tensile properties

Temperature		Time at temperature,	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in
°F	°C	h	ksi	MPa	ksi	MPa	4*D*, %	10^6 psi	GPa	ksi	MPa	ksi	MPa	4*D*, %
–320	–196	...	62	425	48	330	6	...	...	...	...	...	...	...
–112	–80	...	55	380	45	310	6	...	...	...	...	...	...	...
–18	–28	...	54	370	44	305	6	...	...	...	...	...	...	...
75	25	...	52	360	42	290	8	10.4	72	...	...	...	...	...
212	100	0.5	46	315	39	270	10	...	...	...	...	...	...	...
		10	46	315	39	270	10	...	...	...	...	...	...	...
		100	46	315	39	270	10	...	...	...	...	...	...	...
		1,000	46	315	40	275	8	...	...	...	...	...	...	...
		10,000	48	330	45	310	6	...	...	...	...	...	...	...
300	150	0.5	39	270	35	240	10	...	...	...	...	...	...	...
		10	41	285	37	255	9	...	...	...	...	...	...	...
		100	42	290	40	275	7	...	...	...	...	...	...	...
		1,000	38	260	36	250	7	...	...	...	...	...	...	...
		10,000	23	160	21	145	20	...	...	...	...	...	...	...
350	177	0.5	37	255	34	235	7	...	...	...	...	...	...	...
		10	40	275	38	260	6	...	...	...	...	...	...	...
		100	35	240	33	230	7	...	...	...	...	...	...	...
		1,000	22	150	20	140	19	...	...	...	...	...	...	...
		10,000	13	90	11	75	35	...	...	...	...	...	...	...
400	205	0.5	36	250	35	240	6	...	...	52	360	45	310	6
		10	30	205	28	195	7	...	...	44	305	38	260	7
		100	23	160	21	145	23	...	...	35	230	27	185	9
		1,000	12	85	10	70	40	...	...	...	...	...	...	...
		10,000	10	70	7.5	50	50	...	...	...	...	...	...	...
450	230	0.5	31	215	30	205	9	...	...	...	...	...	...	...
		10	19	130	18	125	13	...	...	...	...	...	...	...
		100	14	95	13	90	45	...	...	...	...	...	...	...
500	260	0.5	23	160	22	150	16	...	...	...	...	...	...	...
		10	12	85	11	75	23	...	...	...	...	...	...	...
		100	8.0	55	7.0	50	55	...	...	...	...	...	...	...
600	315	0.5	10	70	9.5	65	35	...	...	...	...	...	...	...

(a) Average of tensile and compressive moduli.
Source data are in English units; metric values are converted and rounded.

Table D4.31 A359.0-T6, -T61 Permanent mold castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4*D*, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4*D*, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
−320	−196	...	60	415	43	295	4	...	...	...	...	...	...	...
−112	−80	...	53	365	41	285	5	...	...	...	...	...	...	...
−18	−28	...	49	340	38	260	6	...	...	...	...	...	...	...
75	25	...	47	325	37	255	7	10.5	72	47	325	37	255	7
212	100	0.5	41	285	34	235	9	...	...	47	325	37	255	7
		10	42	290	35	240	9	...	...	47	325	37	255	7
		100	43	295	35	240	9	...	...	49	340	38	260	7
		1,000	44	305	36	250	9	...	...	52	360	40	275	7
		10,000	46	315	40	275	9	...	...	55	380	48	330	7
300	149	0.5	38	260	33	230	10	...	...	47	325	37	255	7
		10	40	275	35	240	10	...	...	51	350	41	285	7
		100	42	290	38	260	10	...	...	55	380	48	330	7
		1,000	36	250	34	235	11	...	...	49	340	42	290	7
		10,000	18	125	14	95	30	...	...	26	180	17	115	16
350	177	0.5	37	255	33	230	11	...	...	47	325	38	260	7
		10	38	260	36	250	11	...	...	55	380	48	330	7
		100	32	220	30	205	15	...	...	44	305	38	260	7
		1,000	17	115	14	95	35	...	...	26	180	17	115	18
		10,000	13	90	10	70	40	...	...	22	150	12	85	25
400	205	0.5	35	240	33	230	12	...	...	50	345	46	315	7
		10	26	180	24	165	16	...	...	43	295	36	250	9
		100	16	110	14	95	30	...	...	27	185	18	125	18
		1,000	12	85	9.5	66	40	...	...	22	150	12	85	27
		10,000	11	75	8.5	59	45	...	...	20	140	11	75	27
450	230	0.5	28	195	26	180	16	...	...	51	350	44	305	10
		10	14	95	12	85	29	...	...	30	205	20	140	15
		100	11	75	9.0	62	40	...	...	22	150	12	85	28
		1,000	9.5	66	7.5	52	45	...	...	...	...	...	...	...
		10,000	8.5	59	6.5	45	50	...	...	...	...	...	...	...
500	260	0.5	18	125	17	115	25	...	...	37	255	28	195	13
		10	9.5	66	8.5	59	40	...	...	24	165	13	90	25
		100	8.5	59	7.0	48	50	...	...	21	145	10	70	30
		1,000	7.5	52	6.0	41	55	...	...	...	...	...	...	...
		10,000	7.0	48	5.0	34	60	...	...	...	...	...	...	...
600	315	0.5	7.5	52	6.5	45	50	...	...	22	150	12	85	20
		10	6.0	41	5.5	38	60	...	...	21	145	11	75	28
		100	5.5	38	4.4	30	65	...	...	...	...	...	...	...
700	370	0.5	4.4	30	4.0	28	55	...	...	21	145	10	70	28

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.32 359.0-T62 Permanent mold castings: typical tensile properties

Temperature			At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 4*D*, %	10^6 psi	GPa
−320	−196	…	63	435	47	325	4	…	…
−112	−80	…	55	380	47	325	5	…	…
−18	−28	…	52	360	45	310	6	…	…
75	25	…	50	345	42	290	5	10.5	72
300	150	100	42	290	38	260	10	…	…
		1,000	36	250	34	235	11	…	…
		10,000	18	125	14	95	30	…	…
500	260	0.5	18	125	17	115	25	…	…
		10	9.5	66	8.5	59	40	…	…
		100	8.5	59	7.0	48	50	…	…
		1,000	7.5	52	6.0	41	55	…	…
		10,000	7.0	48	5.0	34	60	…	…
600	315	0.5	7.5	52	6.5	45	50	…	…
		10	6.0	41	5.5	38	60	…	…
		100	5.5	38	4.4	30	65	…	…
700	370	0.5	4.4	30	4.0	28	55	…	…

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.33 360.0-F Die castings: typical tensile properties

Temperature			At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength			Modulus of elasticity(a)		Tensile strength		Yield strength		
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 2 in. (50 mm), %	10^6 psi	GPa	ksi	MPa	ksi	MPa	Elongation in 2 in. (50 mm), %
−112	−80	…	50	345	24	165	2	…	…	…	…	…	…	…
−18	−28	…	48	330	25	170	2	…	…	…	…	…	…	…
75	25	…	47	325	25	170	3	10.3	71	47	325	25	170	3
212	100	0.5	44	305	25	170	4	…	…	49	340	26	180	3
		10	44	305	25	170	2	…	…	…	…	…	…	…
		100	44	305	26	180	2	…	…	…	…	…	…	…
		1,000	48	330	32	220	2	…	…	…	…	…	…	…
		10,000	49	340	33	230	2	…	…	…	…	…	…	…
300	150	0.5	41	285	25	170	4	…	…	50	345	27	185	3
		10	43	295	29	200	3	…	…	…	…	…	…	…
		100	44	305	29	200	2	…	…	…	…	…	…	…
		1,000	36	250	28	195	4	…	…	…	…	…	…	…
		10,000	35	240	27	185	4	…	…	…	…	…	…	…
350	177	0.5	38	260	24	165	4	…	…	50	345	30	205	2
		10	39	270	28	195	4	…	…	…	…	…	…	…
		100	34	235	24	165	4	…	…	…	…	…	…	…
		1,000	29	200	21	145	6	…	…	…	…	…	…	…
		10,000	27	185	19	130	6	…	…	…	…	…	…	…
400	205	0.5	34	235	24	165	4	…	…	50	345	34	235	1
		10	31	215	24	165	5	…	…	…	…	…	…	…
		100	28	195	21	145	6	…	…	…	…	…	…	…
		1,000	24	165	16	110	9	…	…	…	…	…	…	…
		10,000	22	150	14	95	10	…	…	…	…	…	…	…
500	260	0.5	23	160	18	125	9	…	…	47	325	30	205	2
		10	21	145	16	110	10	…	…	…	…	…	…	…
		100	18	125	13	90	13	…	…	…	…	…	…	…
		1,000	14	95	9.0	62	17	…	…	…	…	…	…	…
		10,000	11	75	7.0	48	22	…	…	…	…	…	…	…
600	315	0.5	13	90	9.0	62	14	…	…	42	290	25	170	3
		10	12	85	8.0	55	17	…	…	…	…	…	…	…
		100	9.0	62	6.0	41	30	…	…	…	…	…	…	…
		1,000	7.0	48	4.4	30	45	…	…	…	…	…	…	…
		10,000	7.0	48	4.4	30	45	…	…	…	…	…	…	…
700	370	0.5	6.0	41	3.8	26	32	…	…	…	…	…	…	…
		10	4.5	31	2.9	20	34	…	…	…	…	…	…	…
		100	4.4	30	2.8	19	40	…	…	…	…	…	…	…
		1,000	4.4	30	2.8	19	40	…	…	…	…	…	…	…
		10,000	4.4	30	2.8	19	40	…	…	…	…	…	…	…

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.34 360.0-F Die castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated					At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 2 in. (50 mm), %	Tensile strength		Yield strength		Elongation in 2 in. (50 mm), %
°F	°C		ksi	MPa	ksi	MPa		ksi	MPa	ksi	MPa	
−112	−80	...	50	345	24	165	3	...	...	...	...	...
−18	−28	...	48	330	24	165	3	...	...	...	...	...
75	25	...	46	315	24	165	5	46	315	24	165	5
212	100	0.5	39	270	24	165	5	48	330	25	170	6
		10	39	270	24	165	5	...	...	...	...	...
		100	41	285	26	180	5	...	...	...	...	...
		1,000	45	310	32	220	4	...	...	...	...	...
		10,000	45	310	33	230	2	...	...	...	...	...
300	150	0.5	36	250	24	165	9	48	330	27	185	5
		10	39	270	29	200	3	...	...	...	...	...
		100	39	270	29	200	2	...	...	...	...	...
		1,000	36	250	28	195	6	...	...	...	...	...
		10,000	35	240	27	185	7	...	...	...	...	...
350	177	0.5	34	235	24	165	7	49	340	30	205	4
		10	37	255	28	195	4	...	...	...	...	...
		100	33	230	24	165	5	...	...	...	...	...
		1,000	29	200	21	145	9	...	...	...	...	...
		10,000	27	185	19	130	10	...	...	...	...	...
400	205	0.5	32	220	24	165	6	50	345	34	235	4
		10	30	205	24	165	6	...	...	...	...	...
		100	28	195	21	145	9	...	...	...	...	...
		1,000	24	165	16	110	13	...	...	...	...	...
		10,000	22	150	14	95	14	...	...	...	...	...
500	260	0.5	23	160	18	125	13	46	315	30	205	4
		10	21	145	16	110	16	...	...	...	...	...
		100	18	125	13	90	21	...	...	...	...	...
		1,000	14	95	9.0	62	25	...	...	...	...	...
		10,000	11	75	7.0	48	31	...	...	...	...	...
600	315	0.5	13	90	9.0	62	32	41	285	25	170	6
		10	12	85	8.0	55	36	...	...	...	...	...
		100	9.0	62	6.0	41	45	...	...	...	...	...
		1,000	7.0	48	4.4	30	45	...	...	...	...	...
		10,000	7.0	48	4.4	30	45	...	...	...	...	...
700	370	0.5	6.0	41	3.8	26	40	...	...	...	...	...
		10	4.5	31	2.9	20	40	...	...	...	...	...
		100	4.4	30	2.8	19	40	...	...	...	...	...
		1,000	4.4	30	2.8	19	40	...	...	...	...	...
		10,000	4.4	30	2.8	19	40	...	...	...	...	...

Source data are in English units; metric values are converted and rounded.

Table D4.35 380.0-F Die castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated					At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 2 in. (50 mm), %	Tensile strength		Yield strength		Elongation in 2 in. (50 mm), %
°F	°C		ksi	MPa	ksi	MPa		ksi	MPa	ksi	MPa	
−320	−196	···	59	405	30	205	2.5	···	···	···	···	···
−112	−80	···	49	340	22	150	2.5	···	···	···	···	···
−18	−28	···	49	340	23	160	3	···	···	···	···	···
75	25	···	48	330	24	165	3	48	330	24	165	3
212	100	0.5	46	315	24	165	3	46	315	24	165	2
		10	46	315	24	165	3	···	···	···	···	···
		100	46	315	24	165	3	···	···	···	···	···
		1,000	48	330	27	185	3	···	···	···	···	···
		10,000	47	325	29	200	3	···	···	···	···	···
300	150	0.5	40	275	23	160	4	45	310	22	150	2
		10	42	290	24	165	4	···	···	···	···	···
		100	38	260	25	170	4	···	···	···	···	···
		1,000	36	250	24	165	4	···	···	···	···	···
		10,000	34	235	23	160	4	···	···	···	···	···
350	177	0.5	36	250	22	150	4	46	315	23	160	1.5
		10	37	255	23	160	4	···	···	···	···	···
		100	33	230	22	150	4	···	···	···	···	···
		1,000	32	220	21	145	4	···	···	···	···	···
		10,000	31	215	19	130	5	···	···	···	···	···
400	205	0.5	32	220	21	145	5	47	325	24	165	1.5
		10	29	200	20	140	5	···	···	···	···	···
		100	28	195	19	130	6	···	···	···	···	···
		1,000	27	185	17	115	6	···	···	···	···	···
		10,000	26	180	16	110	8	···	···	···	···	···
500	260	0.5	22	150	15	105	11	44	305	21	145	3
		10	21	145	14	95	11	···	···	···	···	···
		100	21	145	13	90	12	···	···	···	···	···
		1,000	17	115	10	70	18	···	···	···	···	···
		10,000	12	83	8.5	59	20	···	···	···	···	···
600	315	0.5	13	90	9.0	62	20	43	295	21	145	2.5
		10	12	85	8.0	55	24	···	···	···	···	···
		100	9.5	66	6.5	45	27	···	···	···	···	···
		1,000	7.0	48	4.6	32	27	···	···	···	···	···
		10,000	7.0	48	3.8	26	28	···	···	···	···	···
700	370	0.5	6.5	45	4.0	28	28	···	···	···	···	···
		10	5.5	38	3.2	22	29	···	···	···	···	···
		100	4.5	31	2.5	17	30	···	···	···	···	···
		1,000	4.5	31	2.5	17	30	···	···	···	···	···
		10,000	4.5	31	2.5	17	30	···	···	···	···	···

Source data are in English units; metric values are converted and rounded.

Table D4.36 380.0-F Die castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated					At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 2 in. (50 mm), %	Tensile strength		Yield strength		Elongation in 2 in. (50 mm), %
°F	°C		ksi	MPa	ksi	MPa		ksi	MPa	ksi	MPa	
−320	−196	...	58	400	29	200	3	...	...	...	...	...
−112	−80	...	48	330	21	145	3	...	...	...	...	...
−18	−28	...	48	330	22	150	3.5	...	...	...	...	...
75	25	...	47	325	23	160	4	47	325	23	160	4
212	100	0.5	44	305	23	160	7	46	315	23	160	4
		10	44	305	24	165	7	...	...	...	...	...
		100	45	310	25	170	7	...	...	...	...	...
		1,000	45	310	29	200	7	...	...	...	...	...
		10,000	46	315	30	205	7	...	...	...	...	...
300	150	0.5	37	255	23	160	10	45	310	20	140	4
		10	39	270	25	170	10	...	...	...	...	...
		100	35	240	24	165	10	49	340	29	200	3.5
		1,000	33	230	22	150	10	...	...	...	...	...
		10,000	31	215	21	145	10	...	...	...	...	...
350	177	0.5	33	230	22	150	11	46	315	22	150	4
		10	34	235	22	150	11	...	...	...	...	...
		100	30	205	20	140	12	...	...	...	...	...
		1,000	29	200	19	130	12	...	...	...	...	...
		10,000	27	185	18	125	13	...	...	...	...	...
400	205	0.5	28	195	20	140	13	47	325	23	160	4
		10	26	180	18	125	13	...	...	...	...	...
		100	25	170	17	115	14	...	...	...	...	...
		1,000	24	165	16	110	15	...	...	...	...	...
		10,000	23	160	15	105	16	...	...	...	...	...
500	260	0.5	19	130	14	95	17	44	305	21	145	5
		10	19	130	14	95	18	...	...	...	...	...
		100	18	125	12	85	20	38	260	17	115	6
		1,000	15	105	9.5	66	30	...	...	...	...	...
		10,000	11	75	7.0	48	31	...	...	...	...	...
600	315	0.5	11	75	8.0	55	26	43	295	21	145	5
		10	11	75	7.5	52	29	...	...	...	...	...
		100	9.0	62	6.0	41	31	...	...	...	...	...
		1,000	6.5	45	4.7	32	45	...	...	...	...	...
		10,000	5.5	38	4.2	29	45	...	...	...	...	...
700	370	0.5	6.0	41	3.9	27	45	...	...	...	...	...
		10	5.0	34	3.2	22	46	...	...	...	...	...
		100	4.7	32	2.8	19	47	...	...	...	...	...
		1,000	4.4	30	2.8	19	50	...	...	...	...	...
		10,000	4.1	28	2.8	19	50	...	...	...	...	...

Source data are in English units; metric values are converted and rounded.

Table D4.37 384.0-F Die castings: typical tensile properties

Temperature			At temperature indicated						
			Tensile strength		Yield strength			Modulus of elasticity(a)	
°F	°C	Time at temperature, h	ksi	MPa	ksi	MPa	Elongation in 2 in. (50 mm), %	10^6 psi	GPa
−320	−196	...	58	400	31	215	1	...	...
−112	−80	...	48	330	23	160	1	...	...
−18	−28	...	48	330	24	165	1	...	...
75	25	...	47	325	25	170	1	10.8	74
212	100	0.5	46	315	25	170	1	10.6	73
		10	46	315	25	170	1	10.6	73
		100	46	315	26	180	1	10.6	73
		1,000	48	330	29	200	1	10.6	73
		10,000	47	325	31	215	1	10.6	73
300	150	0.5	43	295	25	170	2	10.3	71
		10	44	305	28	195	2	10.3	71
		100	41	285	26	180	2	10.3	71
		1,000	39	270	25	170	2	10.3	71
		10,000	37	255	23	160	2	10.3	71
350	177	0.5	40	275	25	170	4	10.0	69
		10	37	255	26	180	4	10.0	69
		100	35	240	23	160	4	10.0	69
		1,000	33	230	22	150	4	10.0	69
		10,000	32	220	20	140	4	10.0	69
400	205	0.5	33	230	23	160	6	9.7	67
		10	31	215	22	150	6	9.7	67
		100	30	205	21	145	6	9.7	67
		1,000	29	200	19	130	6	9.7	67
		10,000	28	195	18	125	6	9.7	67
450	230	0.5	28	195	20	140	8	9.3	64
		10	27	185	19	130	8	9.3	64
		100	27	185	17	115	8	9.3	64
		1,000	25	170	15	105	8	9.3	64
		10,000	21	145	13	90	12	9.3	64
500	260	0.5	24	165	17	115	10	8.6	59
		10	24	165	16	110	10	8.6	59
		100	23	160	14	95	10	8.6	59
		1,000	18	125	11	75	14	8.6	59
		10,000	13	90	8.5	59	23	8.6	59
600	315	0.5	16	110	11	75	16	7.0	48
		10	13	90	8.0	55	22	7.0	48
		100	10	70	6.5	45	26	7.0	48
		1,000	8.0	55	5.0	34	35	7.0	48
		10,000	7.0	48	4.2	29	50	7.0	48
700	370	0.5	7.0	48	3.9	27	28	...	...
		10	6.0	41	3.2	22	40	...	...
		100	5.0	34	2.9	20	50	...	...
		1,000	4.8	33	2.9	20	50	...	...
		10,000	4.8	33	2.9	20	50	...	...

(a) The modulus of elasticity in compression is about 2% greater than in tension.
Source data are in English units; metric values are converted and rounded.

Table D4.38 B443.0-F Sand castings: typical tensile properties

Temperature °F	Temperature °C	Time at temperature, h	At temperature indicated: Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation in 4D, %	Modulus of elasticity(a) 10^6 psi	Modulus of elasticity(a) GPa
−320	−196	...	25	170	10	70	...	...	...
−112	−80	...	19	130	8.0	55	...	...	...
−18	−28	...	19	130	8.0	55	...	...	...
75	25	...	19	130	8.0	55	8	10.3	71
212	100	0.5	16	110	8.0	55	12	...	...
		10	16	110	8.0	55	12	...	...
		100	16	110	8.0	55	10	...	...
		1,000	16	110	8.5	59	8	...	...
		10,000	16	110	11	75	7	...	...
300	150	0.5	14	95	8.0	55	22	...	...
		10	14	95	9.0	62	21	...	...
		100	14	95	10	70	20	...	...
		1,000	14	95	10	70	19	...	...
		10,000	14	95	9.0	62	18	...	...
400	205	0.5	11	75	7.5	52	25	...	...
		10	11	75	8.5	59	24	...	...
		100	11	75	8.0	55	25	...	...
		1,000	11	75	7.5	52	25	...	...
		10,000	11	75	7.5	52	28	...	...
500	260	0.5	9.0	62	6.0	41	30	...	...
		10	9.0	62	6.0	41	30	...	...
		100	9.0	62	6.0	41	30	...	...
		1,000	9.0	62	6.0	41	30	...	...
		10,000	9.0	62	6.0	41	30	...	...
600	315	0.5	6.5	45	4.8	33	30	...	...
		10	6.5	45	4.8	33	32	...	...
		100	6.5	45	4.8	33	35	...	...
		1,000	5.5	38	4.2	29	40	...	...
		10,000	4.0	28	2.8	19	50	...	...
700	370	0.5	4.7	32	3.4	23	35	...	...
		10	3.8	26	2.6	18	40	...	...
		100	3.4	23	2.3	16	55	...	...
		1,000	3.2	22	2.3	16	55	...	...
		10,000	3.2	22	2.3	16	55	...	...

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.39 518.0-F (A218) Sand castings (results of tests made on sand cast test bars): representative tensile properties

Temperature °F	Temperature °C	Time at temperature, h	At temperature indicated: Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation in 4D, %	At room temperature after heating: Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation in 4D, %
75	25	...	36.2	250	20.1	140	8.8	36.2	250	20.1	140	8.8
300	150	100	31.3	215	20.7	145	9	37.1	255	21.9	150	6.5
		1000	32.5	225	21.6	150	6.5	31.5	215	23.2	160	2.8
		5000	34.3	235	20	140	7.4	31.6	220	23.7	165	1.8
400	205	100	25.7	175	18.8	130	9.5	28.3	195	21.5	150	2
		1000	24.5	170	17.2	120	11	24.3	170	19.2	130	1
		5000	23.2	160	15	105	15.5	22.6	155	17.5	120	1.5
500	260	100	19.9	135	13.9	95	14.5	22	150	19.3	135	1
		1000	19.1	130	13.1	90	14	20	140	17.9	125	0.8
		5000	17.8	125	13	90	22	19.6	135	17.7	120	1
600	315	100	13.3	90	9.6	66	18	26.2	180	20.3	140	2.5
		1000	14.9	105	10	70	14.5	34.3	235	21.2	145	6.5
		5000	14.4	100	8.8	61	18	36	250	21.3	145	8

Source data are in English units; metric values are converted and rounded.

Table D4.40 520.0-T4 Sand castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated							At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4D, %	Modulus of elasticity(a)		Tensile strength		Yield strength		Elongation in 4D, %
°F	°C		ksi	MPa	ksi	MPa		10^6 psi	GPa	ksi	MPa	ksi	MPa	
75	25	...	48	330	26	180	16	9.5	66	48	330	26	180	16
212	100	0.5	42	290	24	165	...	...	...	...	...	...	...	...
		10	43	295	24	165	...	...	...	...	...	...	...	...
		100	44	305	25	170	...	...	...	...	...	...	...	...
		1,000	44	305	25	170	...	...	...	...	...	...	...	...
		10,000	44	305	25	170	...	...	...	...	...	...	...	...
300	150	0.5	36	250	22	150	13	...	...	...	...	...	...	...
		10	38	260	23	160	14	...	...	...	...	...	...	...
		100	39	270	23	160	10	...	...	...	...	...	...	...
		1,000	37	255	20	140	13	...	...	...	...	...	...	...
		6,500	...	...	...	...	...	...	...	30	205	29	200	0.5
		10,000	37	255	20	140	13	...	...	...	...	...	...	...
400	205	0.5	29	200	20	140	11	...	...	...	...	...	...	...
		10	27	185	15	105	25	...	...	...	...	...	...	...
		100	24	165	12	85	30	...	...	...	...	...	...	...
		1,000	22	150	12	85	34	...	...	...	...	...	...	...
		2,000	...	...	...	...	...	...	...	28	195	19	130	1
		10,000	21	145	12	85	35	...	...	...	...	...	...	...
500	260	0.5	21	145	7.0	48	20	...	...	...	...	...	...	...
		10	16	110	7.0	48	40	...	...	...	...	...	...	...
		100	15	105	7.0	48	42	...	...	...	...	...	...	...
		1,000	15	105	7.0	48	48	...	...	...	...	...	...	...
		3,000	...	...	...	...	...	...	...	26	180	19	130	1.5
		10,000	15	105	7.0	48	50	...	...	...	...	...	...	...
600	315	0.5	11	75	4.0	28	28	...	...	...	...	...	...	...
		10	11	75	4.0	28	48	...	...	...	...	...	...	...
		100	11	75	4.0	28	52	...	...	...	...	...	...	...
		1,000	11	75	4.0	28	60	...	...	...	...	...	...	...
		10,000	11	75	4.0	28	60	...	...	26	180	19	130	1.5
700	370	0.5	6.5	45	2.0	14	50	...	...	...	...	...	...	...
		10	6.5	45	2.0	14	55	...	...	...	...	...	...	...
		100	6.5	45	2.0	14	60	...	...	...	...	...	...	...
		1,000	6.5	45	2.0	14	70	...	...	...	...	...	...	...
		10,000	6.5	45	2.0	14	70	...	...	26	180	19	130	1.5

(a) Average of tensile and compressive moduli
Source data are in English units; metric values are converted and rounded.

Table D4.41 710.0-F Sand castings: typical tensile properties

Temperature		Time at temperature, h	At temperature indicated					At room temperature after heating				
			Tensile strength		Yield strength		Elongation in 4D, %	Tensile strength		Yield strength		Elongation in 4D, %
°F	°C		ksi	MPa	ksi	MPa		ksi	MPa	ksi	MPa	
−320	−196	...	42(a)	290(a)	35(a)	240(a)	4(a)	...	...	...	...	...
−112	−80	...	37(a)	255(a)	28(a)	195(a)	5(a)	...	...	...	...	...
−18	−28	...	37(a)	255(a)	26(a)	180(a)	6(a)	...	...	...	...	...
75	25	...	35(a)	240(a)	25(a)	170(a)	5(a)	35(a)	240(a)	25(a)	170(a)	5
212	100	0.5	34	235	25	170	5	34	235	25	170	5
		10	35	240	30	205	5	35	240	30	205	5
		100	43	295	38	260	4	44	305	38	260	4
		1,000	46	315	42	290	3	48	330	46	315	3
		10,000	43	295	40	275	3	47	325	44	305	3
300	150	0.5	33	230	25	170	5	35	240	25	170	5
		10	37	255	33	230	3	42	290	38	260	3
		100	34	235	32	220	3	41	285	37	255	3
		1,000	28	195	26	180	6	36	250	30	205	4
		10,000	20	140	17	115	12	29	200	21	145	6
400	205	0.5	24	165	20	140	10	31	215	22	150	5
		10	19	130	17	115	10	30	205	21	145	6
		100	15	105	14	95	14	28	195	19	130	7
		1,000	12	85	10	70	22	23	160	13	90	9
		10,000	10	70	8.0	55	30	21	145	11	75	10
500	260	0.5	13	90	11	75	12	27	185	16	110	10
		10	10	70	8.5	59	23	24	165	11	75	11
		100	8.0	55	7.0	48	33	22	150	9.0	62	12
		1,000	7.0	48	6.0	41	45	20	140	8.0	55	12
		10,000	6.5	45	5.0	34	60	19	130	7.0	48	12

(a) 30 days after casting
Source data are in English units; metric values are converted and rounded.

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J.G. Kaufman, E.L. Rooy, p 243-252
DOI:10.1361/aacp2004p243

DATA SET 5

Creep Rupture Properties

This data set contains the results of uniaxial creep rupture tests of a wide range of aluminum casting alloys conducted at temperatures from 212 to 600 °F (100 to 315 °C).

These data were developed at the Alcoa Research Laboratories in New Kensington, PA, from 1950 through about 1985. The early generation and analysis of the data was led by Kenneth O. Bogardus and Robert C. Malcolm, Jr., with principal testing support from Robert C. Faulk and George Schofield. In more recent years, the activity has been led by Robert J. Bucci and Daniel Lege. Most of the data included here were originally published in Ref 1, although some additional data have been added for this publication.

The tensile tests were made in accordance with ASTM E 139, with ½ in. (12.5 mm) diam tensile specimens per Appendix 3, Fig. A3.1. In most cases, the specimens were as-cast test bars. Strain measurements were made with autographic extensometers used in conjunction with strain-transfer devices.

In most cases, tests were made of several lots of material of each alloy and temper, and the results analyzed and the averages normalized to the room-temperature typical values; in these cases the values are identified as typical values in the table. In some cases, too few data, perhaps only for a single lot, were available, and these are reported as representative rather than typical values.

REFERENCE

1. *Properties of Aluminum Alloys: Tensile, Creep and Fatigue Data at High and Low Temperatures,* J.G. Kaufman, Ed., ASM International, 1999

Table D5.1 201.0-T7 Sand castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
300	150	10	57	395	56	385	56	385	53	365	52	360
		100	51	350	51	350	50	345	49	340	47	325
		1000	45	310	45	310	45	310	44	305	41	285
350	177	1	…	…	…	…	…	…	50	345	48	330
		10	48	330	47	325	46	315	45	310	43	295
		100	42	290	42	290	41	285	39	270	38	260
		1000	35	240	35	240	35	240	34	235	…	…
400	205	1	42	290	42	290	41	285	40	275	39	270
		10	39	270	38	260	38	260	36	250	32	220
		100	33	230	33	230	32	220	30	205	25	170
		1000	25	170	25	170	25	170	…	…	…	…
450	230	10	…	…	…	…	…	…	27	185	24	165
		100	24	165	24	165	23	160	…	…	…	…
500	260	1	…	…	…	…	…	…	…	…	21	145
		10	21	145	20	140	20	140	18	125	…	…

Source data are in English units; metric values are converted and rounded.

Table D5.2 224.0-T7: Creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
300	150	0.1	50	345	46	315	44	305	42	290	41	285
		1	46	315	43	295	41	285	40	275	39	270
		10	41	285	40	275	39	270	37	255	36	250
		100	37	255	36	250	35	240	31	215	…	…
		1000	30	205	28	195	…	…	…	…	…	…
400	205	0.1	39	270	34	235	32	220	28	195	26	180
		1	34	235	29	200	26	180	22	150	20	140
		10	28	195	24	165	21	145	17	115	15	105
		100	23	160	21	145	18	125	…	…	…	…
		1000	19	130	18	125	16	110	…	…	…	…
450	230	0.1	32	220	29	200	26	180	23	160	20	140
		1	28	195	25	170	22	150	16	110	14	95
		10	23	160	21	145	18	125	13	90	11	75
		100	19	130	18	125	15	105	11	75	8.5	59
		1000	15	105	14	95	12	85	…	…	…	…
500	260	0.1	26	180	24	165	23	160	20	140	18	125
		1	23	160	21	145	19	130	16	110	13	90
		10	20	140	18	125	16	110	13	90	10	70
		100	16	110	15	105	13	90	10	70	8.0	55
		1000	11	75	10	70	9.0	62	…	…	…	…
550	290	0.1	22	150	20	140	20	140	17	115	15	105
		1	20	140	18	125	16	110	14	95	12	85
		10	17	115	15	105	14	95	12	85	9.5	66
		100	13	90	12	85	10	70	8.0	55	7.0	48
		1000	8.0	55	6.5	45	…	…	…	…	…	…
600	315	0.1	19	130	17	115	17	115	15	105	13	90
		1	17	115	15	105	14	95	13	90	11	75
		10	14	95	12	85	12	85	10	70	8.0	55
		100	10	70	9.0	62	6.5	45	…	…	…	…
		1000	5.0	34	3.5	24	…	…	…	…	…	…
650	345	0.1	16	110	15	105	14	95	12	85	11	75
		1	14	95	12	85	12	85	9.5	66	8.0	55
		10	10	70	9.5	66	8.0	55	6.0	41	5.5	38
		100	7.0	48	6.0	41	4.3	30	…	…	…	…
		1000	3.0	21	2.0	14	…	…	…	…	…	…
700	370	0.1	14	95	12	85	11	75	8.5	59	7.5	52
		1	11	75	10	70	8.0	55	6.3	43	5.0	34
		10	7.0	48	6.5	45	4.3	30	3.3	23	2.5	17
		100	4.0	28	…	…	…	…	…	…	…	…

Source data are in English units; metric values are converted and rounded.

Table D5.3 240.0-F Sand castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
400	205	0.1	31	215	30	205	29	200	28	195	23	160
		1	30	205	29	200	28	195	22	150	18	125
		10	28	195	26	180	22	150	18	125	14	95
		100	22	150	18	125	16	110	13	90	11	75
		1000	16	110	12	85	11	75	10	70	8.5	59
500	260	0.1	27	185	20	140	17	115	13	90	10	70
		1	20	140	15	105	13	90	9.0	62	6.5	45
		10	15	105	11	75	9.0	62	6.5	45	5.0	34
		100	11	75	7.5	52	6.5	45	4.5	31	4.0	28
		1000	8.0	55	5.5	38	4.5	31	4.0	28	3.0	21
600	315	0.1	19	130	13	90	10	70	6.5	45	4.5	31
		1	13	90	8.0	55	6.5	45	4.0	28	2.5	17
		10	8.0	55	5.0	34	4.0	28	2.5	17	1.5	10
		100	5.0	34	3.0	21	2.5	17	1.5	10	1.0	7.0
		1000	3.0	21	2.0	14	1.5	10	1.0	7.0	0.5	3.0

Source data are in English units; metric values are converted and rounded.

Table D5.4 242.0-T77 Sand castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
300	150	1	...	...	26	180	21	145	...	...	...	...
		10	...	...	26	180	21	145	...	...	...	...
		100	27	185	25	170	21	145	...	...	...	...
		1000	22	150	20	140	18	125	...	...	...	...
400	205	1	...	...	20	140	17	115	14	95	...	...
		10	19	130	17	115	15	105	12	85	...	...
		100	16	110	14	95	12	85	...	...	...	...
		1000	13	90	12	85	...	...	...	...	...	...
600	315	1	...	...	...	...	...	...	3.5	24	2.8	19
		10	...	...	...	...	...	...	3.1	21	2.4	17
		100	3.8	26	3.6	25	3.3	23	2.6	18	1.9	13
		1000	3.2	22	2.7	19	2.3	16	1.5	10	1.2	8.0

Source data are in English units; metric values are converted and rounded.

Table D5.5 249.0-T7: Creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
300	150	0.1	53	365	51	350	51	350	50	345	50	345
		1	51	350	50	345	49	340	49	340	48	330
		10	48	330	48	330	47	325	47	325	44	305
		100	43	295	...	...	...	...	...	...	...	...
350	177	0.1	48	330	47	325	46	315	45	310	45	310
		1	46	315	45	310	44	305	43	295	41	285
		10	41	285	40	275	39	270	38	260	35	240
		100	33	230	33	230	32	220	30	205	25	170
		1000	25	170	24	165	24	165	20	140	17	115
400	205	0.1	42	290	41	285	40	275	39	270	37	255
		1	38	260	37	255	36	250	35	240	33	230
		10	32	220	31	215	31	215	29	200	25	170
		100	26	180	25	170	24	165	21	145	15	105
		1000	20	140	19	130	18	125	15	105	12	85

Source data are in English units; metric values are converted and rounded.

Table D5.6 295.0-T6 Sand castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
75	25	100	40(a)	275(a)	...	...	...	...	...	...	...	...
		1000	39(a)	270(a)	...	...	...	...	...	...	...	...
212	100	1	...	...	31	215	27	185	...	...	...	...
		10	...	...	30	205	26	180	...	...	...	...
		100	32	220	30	205	26	180	...	...	...	...
		1000	31	215	...	...	26	180	...	...	...	...
300	150	1	...	...	28	195	26	180	17	115	...	...
		10	30	205	28	195	25	170	17	115	...	...
		100	27	185	27	185	24	165	15	105	...	...
		1000	20	140	...	...	16	110	...	...	...	...
400	205	1	...	...	...	...	...	...	15	105	8.0	55
		10	...	...	18	125	16	110	8.0	55	...	...
		100	16	110	14	95	9.5	66	...	...	...	...
		1000	11	75	11	75	5.8	40	...	...	...	...

(a) Tested at 90 °F (32 °C)
Source data are in English units; metric values are converted and rounded.

Table D5.7 333.0-T533 Permanent mold castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa
212	100	1	28	195	28	195	25	170
		10	27	185	...	...	...	...
		100	26	180	...	...	...	...
		1000	26	180	...	...	...	...
300	150	1	23	160	23	160	22	150
		10	22	150	22	150	22	150
		100	22	150	22	150	22	150
		1000	22	150	21	145	...	...
400	205	1	21	145	21	145	17	115
		10	19	130	19	130	15	105
		100	17	115	16	110	...	...
		1000	14	95	...	...	...	...

Source data are in English units; metric values are converted and rounded.

Table D5.8 336.0-T551 Permanent mold castings: creep rupture and creep properties

Temperature			Rupture stress	
°F	°C	Time under stress, h	ksi	MPa
75	25	0.1	36	250
		1	36	250
		10	36	250
		100	36	250
		1000	36	250
212	100	0.1	32	220
		1	32	220
		10	32	220
		100	32	220
		1000	32	220
300	150	0.1	27	185
		1	26	180
		10	26	180
		100	26	180
		1000	25	170
350	177	0.1	24	165
		1	23	160
		10	23	160
		100	22	150
		1000	20	140
400	205	0.1	21	145
		1	20	140
		10	19	130
		100	18	125
		1000	15	105
500	260	1000	7.0	48
600	315	1000	2.8	19

Source data are in English units; metric values are converted and rounded.

Table D5.9 A344.0-T4 Permanent mold castings (results of tests on permanent mold test bars): creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
75	25	0.1	22	150	21	145	20	140	18	125	16	110
		1	22	150	19	130	18	125	16	110	15	105
		10	21	145	16	110	15	105	14	95	12	85
		100	19	130	14	95	13	90	11	75	10	70
		1000	17	115	12	85	11	75	10	70	9.5	66

Source data are in English units; metric values are converted and rounded.

Table D5.10 354.0-T6, -T61 Permanent mold castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
350	177	0.1	44	305	43	295	41	285	39	270	37	255
		1	43	295	42	290	41	285	39	270	37	255
		10	41	285	41	285	40	275	37	255	35	240
		100	35	240	34	235	33	230	30	205	17	115
		1000	25	170	24	165	24	165	20	140	11	75
400	205	0.1	41	285	40	275	39	270	37	255	35	240
		1	37	255	36	250	36	250	34	235	31	215
		10	32	220	31	215	30	205	26	180	18	125
		100	23	160	23	160	22	150	18	125	10	70
		1000	13	90	13	90	12	85	12	85	7.0	48

Source data are in English units; metric values are converted and rounded.

Table D5.11 355.0-T51 Sand castings: creep rupture and creep properties

Temperature		Time under stress, h	Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C		ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
400	205	1	...	...	10(a)	70(a)	9.6(a)	66(a)	8.6(a)	59(a)	...	...
		10	10(a)	70(a)	9.6(a)	66(a)	9.0(a)	62(a)	8.0(a)	55(a)	...	...
		100	9.6(a)	66(a)	8.9(a)	61(a)	8.2(a)	57(a)	7.0(a)	48(a)	...	...
		1000	8.6(a)	59(a)	7.8(a)	54(a)	7.0(a)	48(a)	5.0(a)	34(a)	...	...
600	315	1	...	...	3.0(b)	21(b)	2.9(b)	20(b)	2.5(b)	17(b)	2.0(b)	14(b)
		10	3.2(b)	22(b)	2.7(b)	19(b)	2.5(b)	17(b)	2.1(b)	14(b)	1.7(b)	12(b)
		100	2.6(b)	18(b)	2.4(b)	17(b)	2.2(b)	15(b)	1.8(b)	12(b)	1.4(b)	10(b)
		1000	2.1(b)	14(b)	1.9(b)	13(b)	1.7(b)	12(b)	1.5(b)	10(b)	...	...

(a) Heated for 100 days at 400 °F (205 °C) before testing. (b) Heated for 40 days at 600 °F (315 °C) before testing
Source data are in English units; metric values are converted and rounded.

Table D5.12 355.0-T62 Permanent mold castings: creep rupture and creep properties

Temperature		Time under stress, h	Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C		ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
75	25	0.1	43(a)	295(a)	...	...	...	...	...	...	...	...
		1	42(a)	290(a)	...	...	...	...	...	...	...	...
		10	41(a)	285(a)	...	...	...	...	...	...	...	...
		100	40(a)	275(a)	...	...	...	...	...	...	...	...
		1000	40(a)	275(a)	...	...	...	...	...	...	...	...
212	100	1	39	270	38	260	36	250	...	...	...	...
		10	38	260	37	255	35	240	...	...	...	...
		100	38	260	36	250	34	235	...	...	...	...
		1000	37	255	35	240	33	230	...	...	...	...
300	150	1	34	235	...	...	32	220	20	140	...	...
		10	32	220	...	...	31	215	...	...	...	...
		100	31	215	...	...	30	205	...	...	...	...
		1000	29	200	...	...	25	170	...	...	...	...
400	205	1	...	...	...	...	19	130	15	105	10	70
		10	...	...	...	...	18	125	13	90	8.0	55
		100	18	125	...	...	16	110	9.5	66	...	...
		1000	13	90	...	...	12	85	8.0	55	...	...

(a) Tested at 90 °F (32 °C)
Source data are in English units; metric values are converted and rounded.

Table D5.13 355.0-T71 Permanent mold castings: creep rupture and creep properties

Temperature		Time under stress, h	Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C		ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
75	25	1	38(a)	260(a)	...	...	...	...	...	...	...	...
		10	38(a)	260(a)	...	...	...	...	...	...	...	...
		100	37(a)	255(a)	...	...	...	...	...	...	...	...
		1000	37(a)	255(a)	...	...	...	...	...	...	...	...
212	100	1	...	...	29	200	...	...	...	...	...	...
		10	32	220	29	200	...	...	...	...	...	...
		100	31	215	28	195	...	...	...	...	...	...
		1000	29	200	27	185	...	...	...	...	...	...
300	150	1	28	195	26	180	24	165	...	...	...	...
		10	27	185	25	170	23	160	...	...	...	...
		100	25	170	24	165	22	150	...	...	...	...
		1000	24	165	22	150	21	145	...	...	...	...
400	205	1	...	...	...	...	20	140	15	105	12	85
		10	21	145	20	140	18	125	14	95	11	75
		100	18	125	17	115	16	110	13.5	95	...	...
		1000	14	95	13	90	12.5	85	...	...	...	...

(a) Tested at 90 °F (32 °C)
Source data are in English units; metric values are converted and rounded.

Table D5.14 355.0-T71 Sand castings: creep rupture and creep properties

Temperature °F	Temperature °C	Time under stress, h	Rupture stress ksi	Rupture stress MPa	Stress at 1.0% creep ksi	Stress at 1.0% creep MPa	Stress at 0.5% creep ksi	Stress at 0.5% creep MPa	Stress at 0.2% creep ksi	Stress at 0.2% creep MPa	Stress at 0.1% creep ksi	Stress at 0.1% creep MPa
75	25	0.1	32(a)	220(a)	31(a)	215(a)	...	...	...	...	...	...
		1	32(a)	220(a)	31(a)	215(a)	...	...	...	...	...	...
		10	32(a)	220(a)	31(a)	215(a)	...	...	...	...	...	...
		100	32(a)	220(a)	31(a)	215(a)	...	...	...	...	...	...
		1000	31(a)	215(a)	31(a)	215(a)	...	...	...	...	...	...
212	100	1	...	...	28	195	...	...	...	...	...	...
		10	28	195	27.5	190	...	...	...	...	...	...
		100	27.5	190	27	185	...	...	...	...	...	...
		1000	27	185	26	180	...	...	...	...	...	...
300	150	1	25	170	24	165	22	150	...	...	...	...
		10	24	165	23	160	21	145	...	...	...	...
		100	23	160	22	150	20	140	...	...	...	...
		1000	22	150	21	145	...	...	...	...	...	...
400	205	1	21	145	21	145	19	130	15	105	12	85
		10	20	140	19	130	17	115	14	95	...	...
		100	18	125	17	115	16	110	13.5	95	...	...
		1000	14	95	...	...	...	...	...	...	...	...

(a) Tested at 90 °F (32 °C)
Source data are in English units; metric values are converted and rounded.

Table D5.15 A355.0-T51 Sand castings: creep rupture and creep properties

Temperature °F	Temperature °C	Time under stress, h	Rupture stress ksi	Rupture stress MPa	Stress at 1.0% creep ksi	Stress at 1.0% creep MPa	Stress at 0.5% creep ksi	Stress at 0.5% creep MPa	Stress at 0.2% creep ksi	Stress at 0.2% creep MPa	Stress at 0.1% creep ksi	Stress at 0.1% creep MPa
400	205	1	...	...	...	...	16	110	10.5	70	...	...
		10	16.8	115	16	110	15	105	10	70	...	...
		100	15	105	14.5	100	13	90	9.4	65	...	...
		1000	12.3	85	11	75	...	...	8.8	61	...	...
600	315	0.1	10	70	9.0	62	8.0	55	6.0	41	4.4	30
		1	8.5	59	7.0	48	6.5	45	4.8	33	3.8	26
		10	7.0	48	5.5	38	5.0	34	3.9	27	3.3	23
		100	5.5	38	4.6	32	4.0	28	3.2	22	2.9	20
		1000	4.2	29	3.7	26	3.2	22	2.7	19	2.5	17

Source data are in English units; metric values are converted and rounded.

Table D5.16 C355.0-T6: Creep rupture and creep properties

Temperature °F	Temperature °C	Time under stress, h	Rupture stress ksi	Rupture stress MPa	Stress at 1.0% creep ksi	Stress at 1.0% creep MPa	Stress at 0.5% creep ksi	Stress at 0.5% creep MPa	Stress at 0.2% creep ksi	Stress at 0.2% creep MPa	Stress at 0.1% creep ksi	Stress at 0.1% creep MPa
300	150	0.1	41	285	39	270	38	260	36	250	34	235
		1	40	275	39	270	38	260	35	240	33	230
		10	39	270	38	260	37	255	34	235	32	220
		100	38	260	37	255	36	250	33	230	31	215
		1000	33	230	33	230	32	220	28	195	27	185
350	177	0.1	39	270	38	260	38	260	35	240	34	235
		1	37	255	37	255	36	250	34	235	33	230
		10	35	240	35	240	35	240	32	220	31	215
		100	32	220	32	220	31	215	30	205	28	195
		1000	22	150	22	150	21	145	19	130	16	110
400	205	0.1	37	255	36	250	36	250	34	235	33	230
		1	35	240	35	240	34	235	31	215	30	205
		10	30	205	30	205	29	200	26	180	21	145
		100	22	150	22	150	21	145	19	130	9.5	66
		1000	14	95	14	95	14	95	13	90	...	...
500	260	0.1	24	165	...	...	...	...	...	...	...	...
		1	18	125	...	...	...	...	...	...	...	...
		10	13	90	...	...	...	...	...	...	...	...
		100	9.0	62	...	...	...	...	...	...	...	...
		1000	6.5	45	...	...	...	...	...	...	...	...

Source data are in English units; metric values are converted and rounded.

Table D5.17 356.0-T7 Sand castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
75	25	1	30(a)	205(a)	28(a)	195(a)	26(a)	180(a)	…	…	…	…
		10	29(a)	200(a)	28(a)	195(a)	26(a)	180(a)	…	…	…	…
		100	28(a)	195(a)	27(a)	185(a)	25(a)	170(a)	…	…	…	…
		1000	28(a)	195(a)	26(a)	180(a)	25(a)	170(a)	…	…	…	…
212	100	1	…	…	25	170	23.5	160	…	…	…	…
		10	25	170	24.5	170	23.5	160	…	…	…	…
		100	24.5	169	24	165	22.5	155	…	…	…	…
		1000	24	165	23.5	160	22	150	…	…	…	…
300	150	1	23	160	22.5	155	21.5	150	17	115	…	…
		10	22.5	155	22	150	21	145	16.5	115	…	…
		100	22	150	21.5	150	20.5	140	16	110	…	…
		1000	20	140	19.5	135	19	130	15	105	…	…
400	205	0.1	21	145	…	…	…	…	…	…	…	…
		1	20	140	…	…	…	…	15	105	9.5	66
		10	18	125	18	125	17	115	14	95	7.8	54
		100	15	105	15	105	14	95	10	70	5.0	34
		1000	8.5	59	…	…	…	…	5.5	38	…	…

(a) Tested at 90 °F (32 °C)
Source data are in English units; metric values are converted and rounded.

Table D5.18 A356.0-T6, -T61 Permanent mold castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
300	150	0.1	34	235	31	215	30	205	28	195	27	185
		1	34	235	31	215	29	200	27	185	26	180
		10	33	230	30	205	28	195	26	180	25	170
		100	29	200	28	195	27	185	25	170	24	165
		1000	24	165	24	165	23	160	…	…	…	…

Source data are in English units; metric values are converted and rounded.

Table D5.19 A357.0-T6, -T61, -T62 Permanent mold castings: creep rupture and creep properties

Temperature		Time under	Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
350	177	0.1	36	250	35	240	35	240	32	220	31	215
		1	35	240	34	235	34	235	31	215	30	205
		10	33	230	32	220	31	215	29	200	26	180
		100	25	170	25	170	24	165	20	140	…	…
		1000	16	110	16	110	16	110	…	…	…	…

Source data are in English units; metric values are converted and rounded.

Table D5.20 360.0-F Die castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
212	100	0.1	43	295	42	290	41	285	35	240	28	195
		1	43	295	42	290	38	260	32	220	27	185
		10	42	290	40	275	37	255	30	205	26	180
		100	42	290	38	260	35	240	28	195	25	170
		1000	41	285	36	250	33	230	26	180	24	165
300	150	0.1	39	270	37	255	35	240	32	220	29	200
		1	38	260	35	240	33	230	29	200	27	185
		10	35	240	33	230	31	215	26	180	18	125
		100	32	220	30	205	27	185	17	115	4.0	28
		1000	27	185	25	170	22	150	18	125	…	…
400	205	0.1	33	230	31	215	29	200	26	180	23	160
		1	29	200	27	185	25	170	21	145	18	125
		10	25	170	23	160	21	145	17	115	13	90
		100	21	145	19	130	17	115	13	90	8.5(a)	59(a)
		1000	16	110	15	105	13	90	10	70	7.0(a)	48(a)

(a) These values are higher than the corresponding values for 300 °F (150 °C). This behavior is probably associated with aging.
Source data are in English units; metric values are converted and rounded.

Table D5.21 380.0-F Die castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
212	100	0.1	45	310	44	305	42	290	38	260	31	215
		1	44	305	43	295	40	275	35	240	28	195
		10	42	290	41	285	38	260	31	215	25	170
		100	41	285	38	260	35	240	27	185	23	160
		1000	39	270	36	250	31	215	23	160	21	145
300	150	0.1	39	270	38	260	36	250	31	215	25	170
		1	37	255	36	250	33	230	27	185	23	160
		10	34	235	31	215	28	195	23	160	20	140
		100	29	200	26	180	23	160	16	110	5.0	34
		1000	24	165	23	160	20	140	10	70	…	…
400	205	0.1	28	195	26	180	23	160	19	130	17	115
		1	25	170	21	145	20	140	17	115	15	105
		10	22	150	19	130	17	115	15	105	13	90
		100	19	130	17	115	15	105	13	90	11(a)	75(a)
		1000	16	110	15	105	13	90	11(a)	75(a)	10(a)	70(a)

(a) These values are higher than the corresponding values for 300 °F (150 °C). This behavior is probably associated with aging.
Source data are in English units; metric values are converted and rounded.

Table D5.22 384.0-F Die castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
300	150	0.1	43	295	41	285	37	255	30	205	…	…
		1	42	290	37	255	34	235	…	…	…	…
		10	38	260	33	230	30	205	…	…	…	…
		100	33	230	29	200	…	…	…	…	…	…
		1000	28	195	…	…	…	…	…	…	…	…
400	205	0.1	31	215	29	200	26	180	21	145	18	125
		1	29	200	25	170	22	150	16	110	…	…
		10	26	180	21	145	18	125	…	…	…	…
		100	23	160	19	130	16	110	…	…	…	…
		1000	21	145	17	115	14	95	…	…	…	…

Source data are in English units; metric values are converted and rounded.

Table D5.23 B443.0-F Sand castings: creep rupture and creep properties

Temperature			Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C	Time under stress, h	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
75	25	1	19(a)	130(a)	…	…	…	…	…	…	…	…
		10	18(a)	125(a)	…	…	…	…	…	…	…	…
		100	17(a)	115(a)	…	…	…	…	…	…	…	…
		1000	16(a)	110(a)	…	…	…	…	…	…	…	…
212	100	1	16	110	…	…	…	…	…	…	…	…
		10	15	105	…	…	…	…	…	…	…	…
		100	14	95	…	…	…	…	…	…	…	…
		1000	14	95	…	…	…	…	…	…	…	…
300	150	1	13	90	10	70	9.0	62	7.0	48	…	…
		10	13	90	10	70	9.0	62	7.0	48	…	…
		100	12	85	10	70	8.5	59	6.5	45	…	…
		1000	10	70	9.0	62	7.0	48	…	…	…	…
400	205	1	…	…	9.0	62	8.0	55	7.0	48	4.9	34
		10	9.5	66	8.5	59	7.5	52	4.9	34	…	…
		100	8.0	55	7.0	48	6.0	41	…	…	…	…
		1000	6.5	45	6.0	41	5.0	34	…	…	…	…

(a) Tested at 90 °F (32 °C)
Source data are in English units; metric values are converted and rounded.

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DOI:10.1361/aacp2004p253

DATA SET 6

Rotating-Beam Reversed-Bending Fatigue Curves

This data set contains the results of rotating-beam reversed-bending (stress ratio, $R = -1.0$) fatigue tests for a wide range of aluminum casting alloys. All the fatigue curves were developed at Alcoa Laboratories in New Kensington, PA.

These fatigue curves are the results of tests on individual lots of material considered representative of the respective alloys and tempers. The tests were made in R.R. Moore type rotating-beam fatigue machines. The raw data are presented; they have not been normalized to any typical or average properties for the individual alloys and tempers. In some cases, the results of tests from several lots of the same alloy and temper are included on one figure.

Unless otherwise noted, the tests are performed on smooth and notched specimens as shown in Fig. A3.2 of Appendix 3.

A horizontal arrow on a rightmost data point indicates that the specimen did not fail.

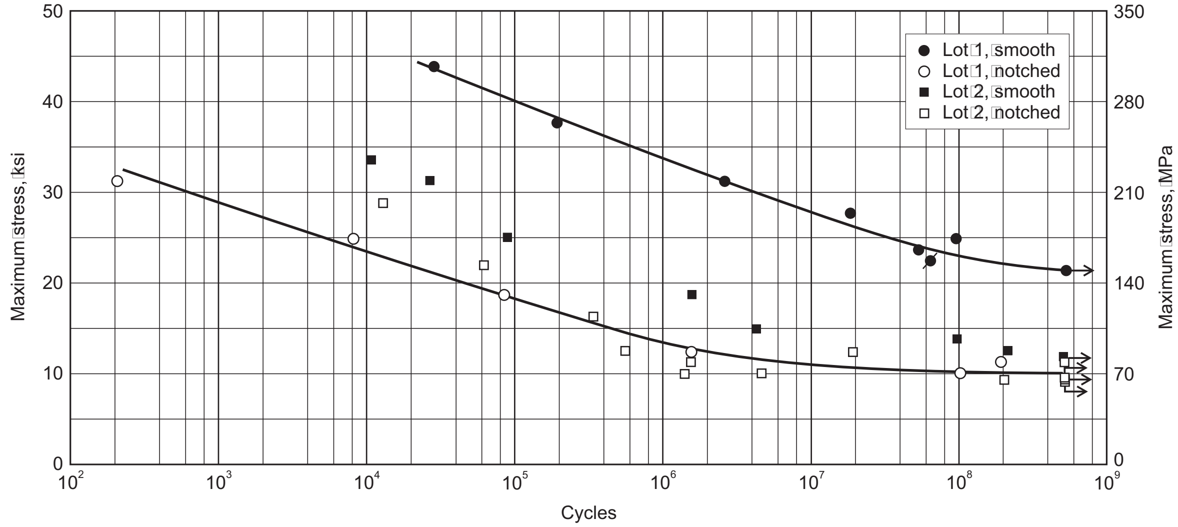

Fig. D6.1 213.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from two lots. Line through data point indicates specimen had nonuniform microstructure.

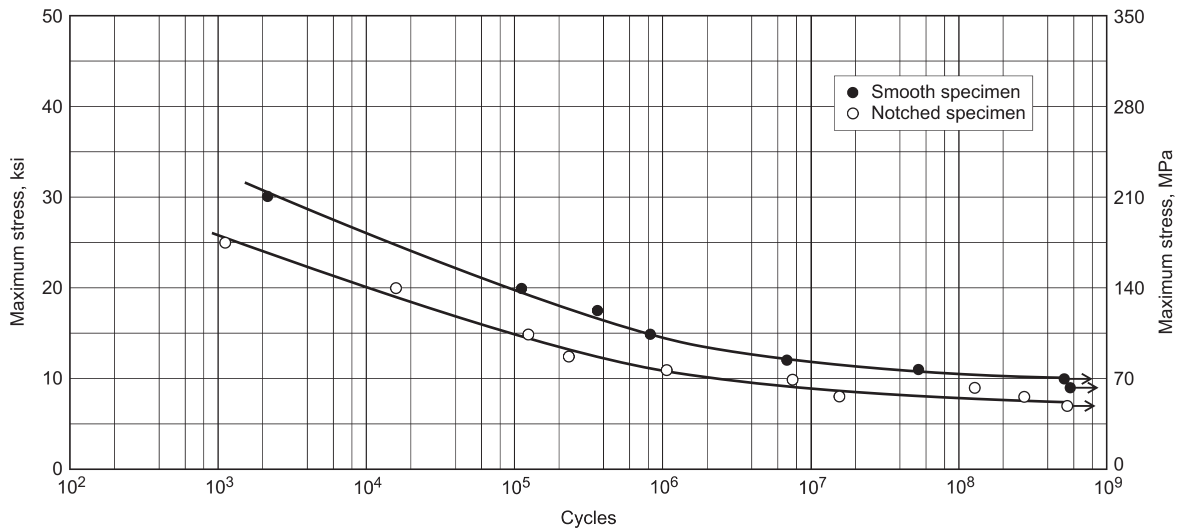

Fig. D6.2 213.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

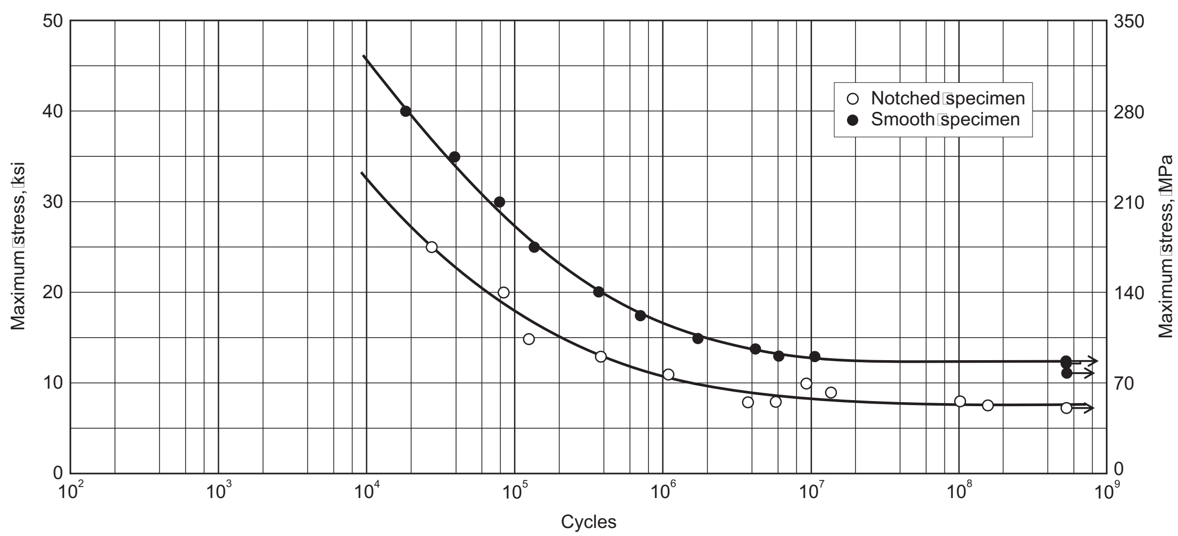

Fig. D6.3 224.0-T62, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

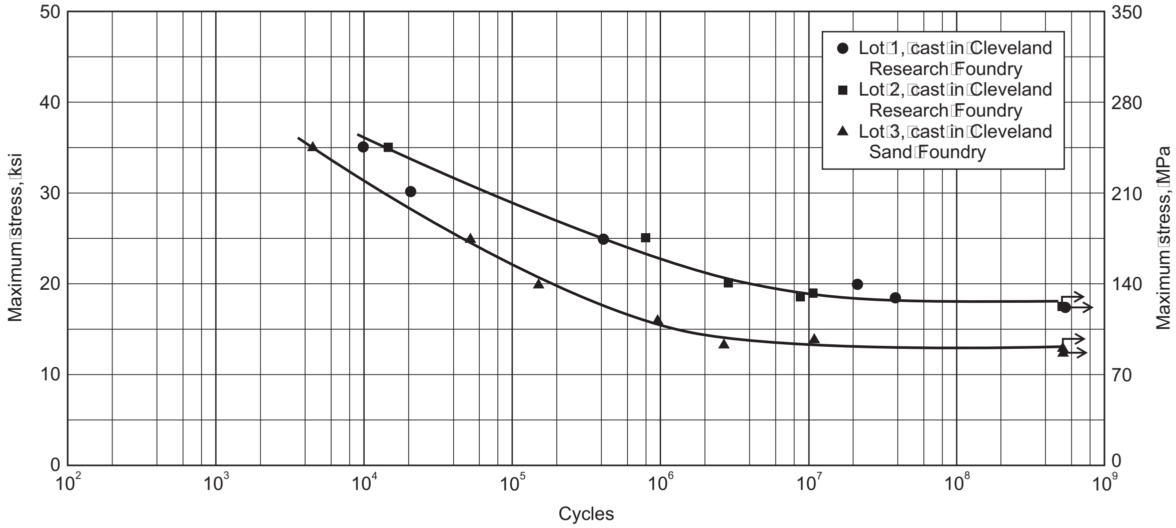

Fig. D6.4 240.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from three lots

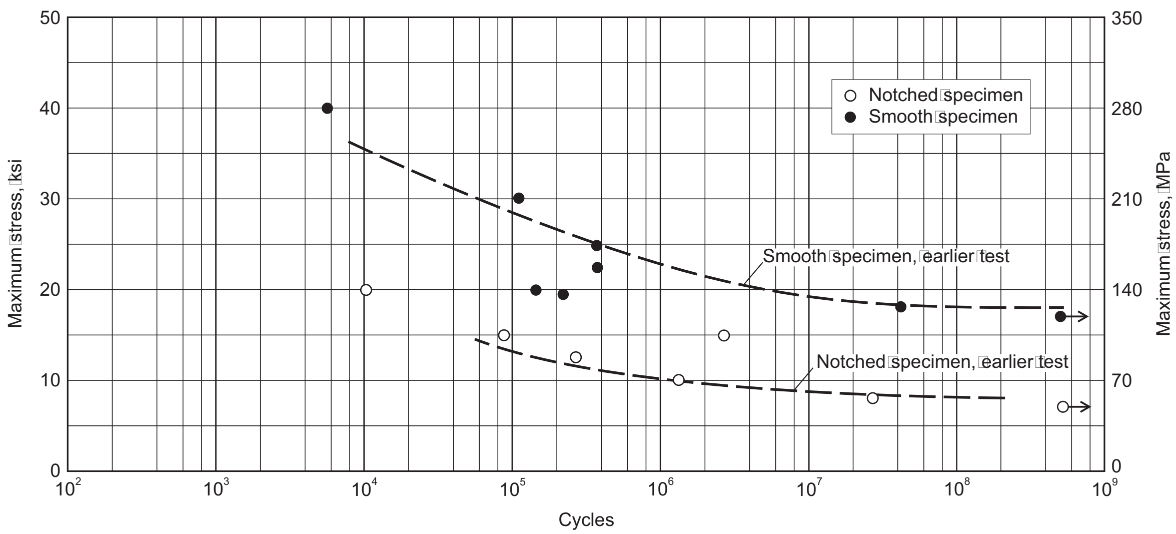

Fig. D6.5 240.0-F, sand cast aluminum casting rotating-beam fatigue curve. Data points for smooth and notched specimens from one lot are compared to curves from previous tests.

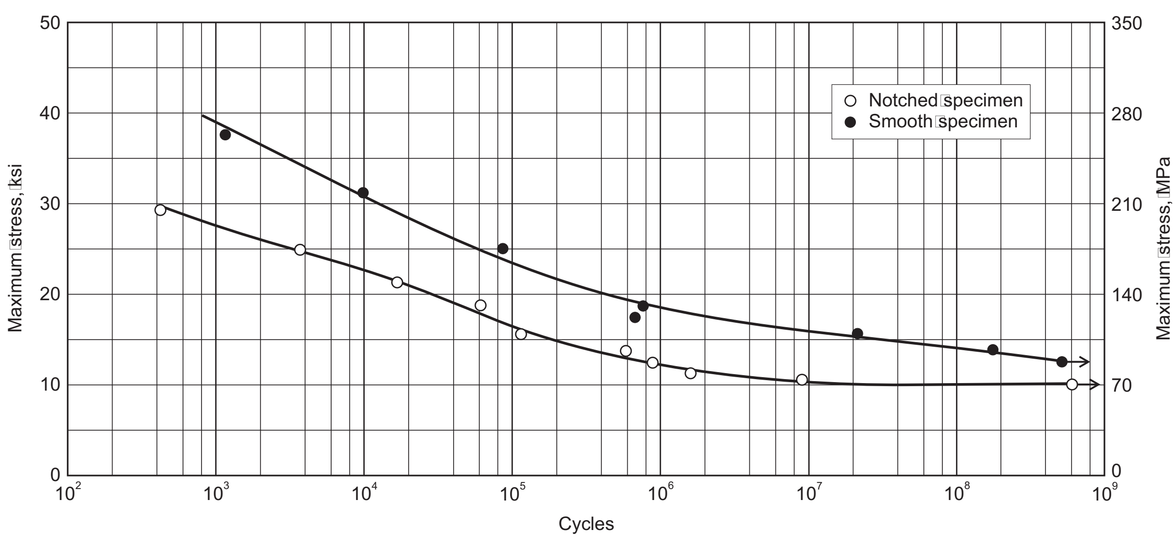

Fig. D6.6 242.0-O, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

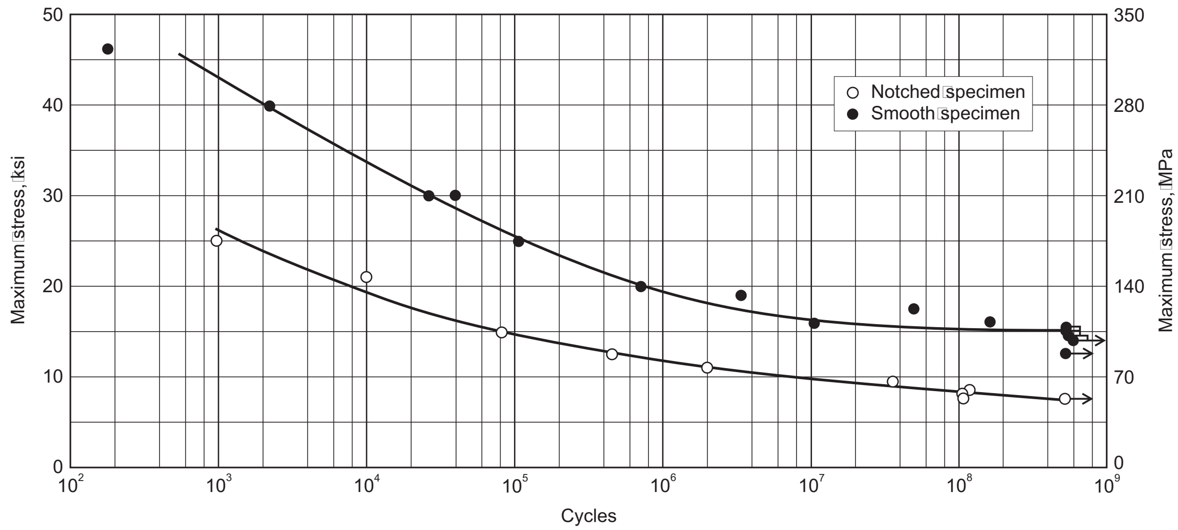

Fig. D6.7 242.0-T571, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

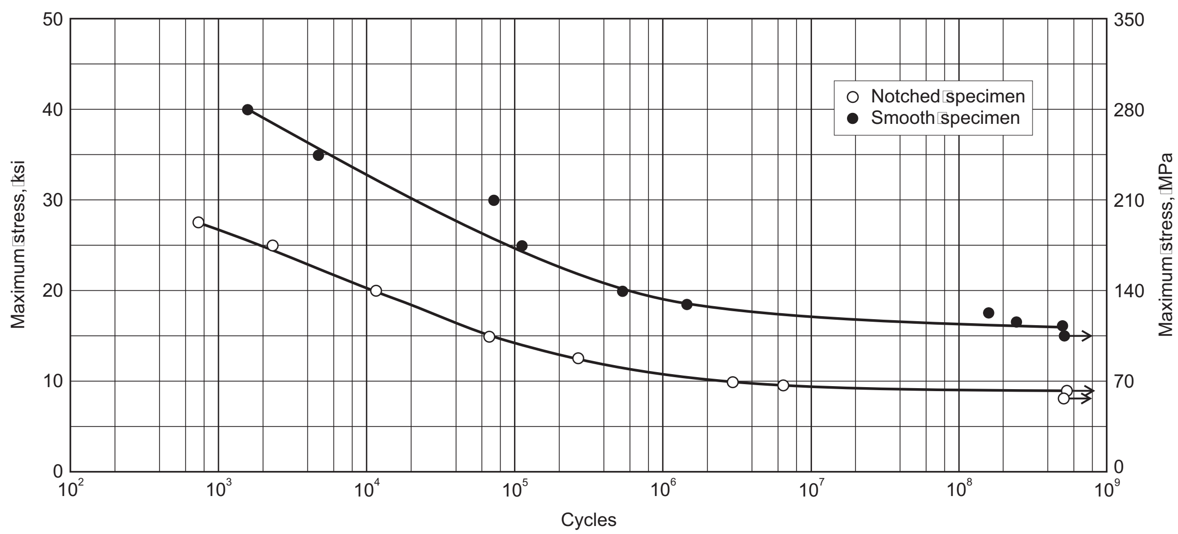

Fig. D6.8 242.0-T571, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

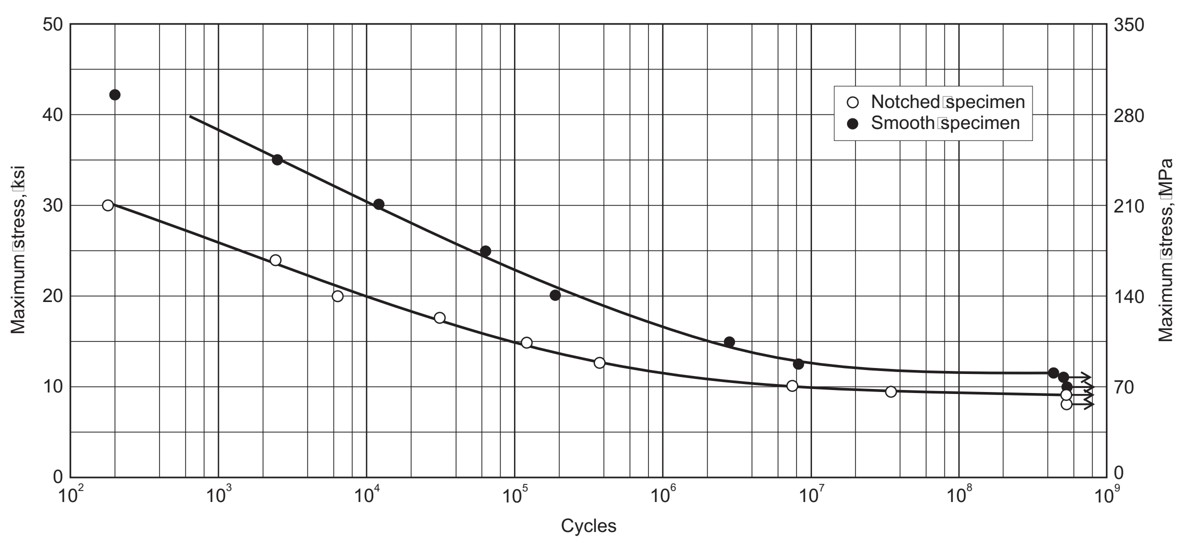

Fig. D6.9 242.0-T571, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

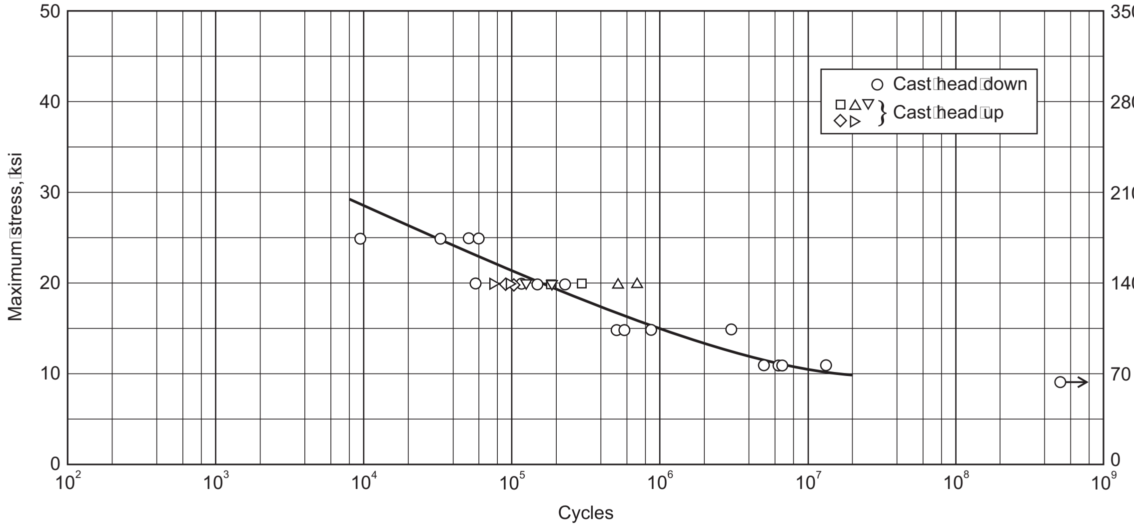

Fig. D6.10 242.0-T571, cast pistons aluminum casting rotating-beam fatigue curve. Smooth specimens are from the wrist pin boss, shaped to Fig. A3.2(a), Appendix 3. Open circle symbol, cast head down, others cast head up

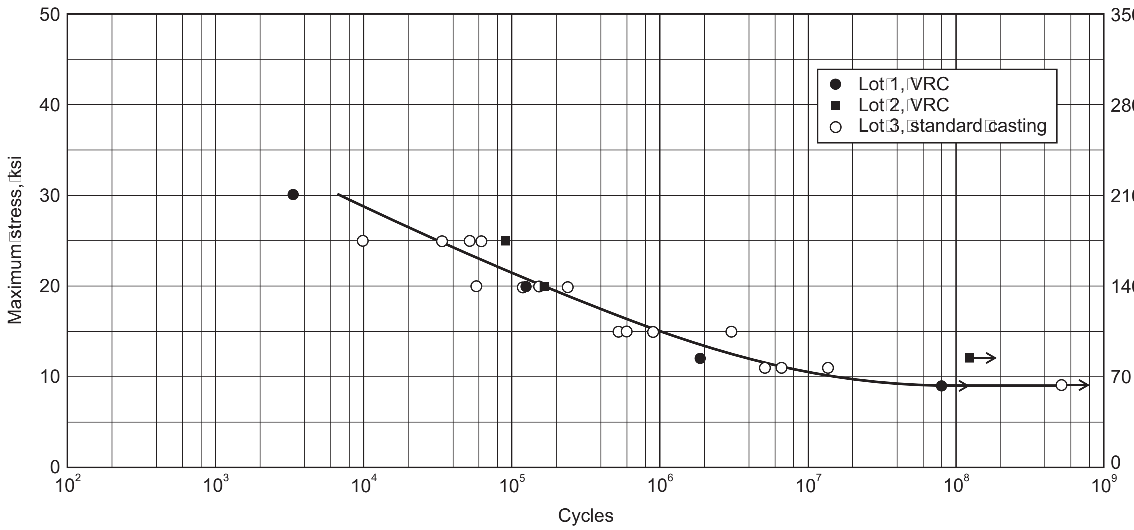

Fig. D6.11 242.0-T571, cast pistons aluminum casting rotating-beam fatigue curve. Smooth specimens are from the wrist pin boss, shaped to Fig. A3.2(a), Appendix 3. Solid symbols are vacuum riserless castings (VRC); open symbol is standard.

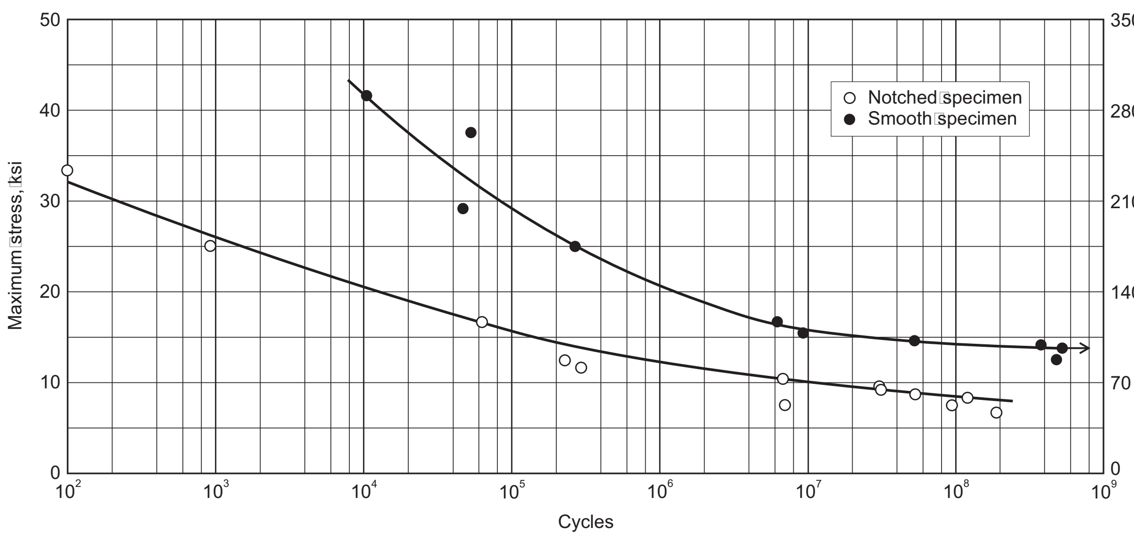

Fig. D6.12 242.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

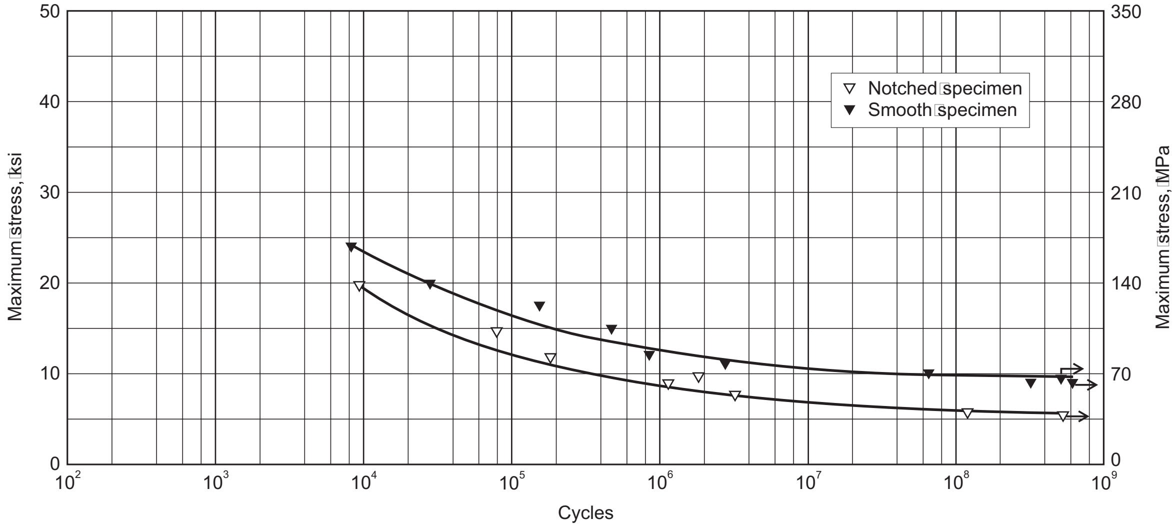

Fig. D6.13 242.0-T75, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

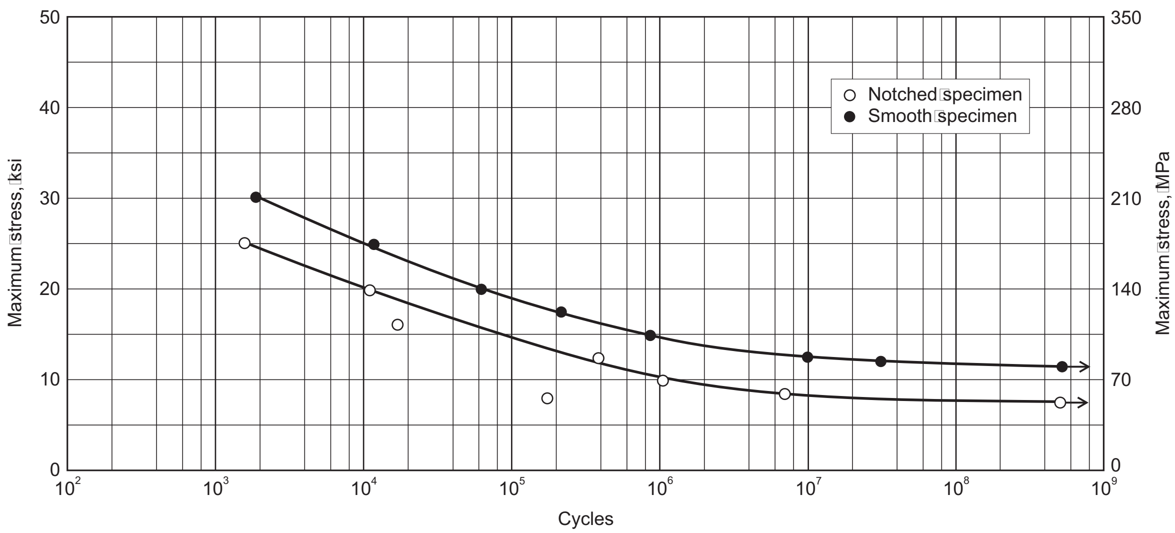

Fig. D6.14 242.0-T77, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

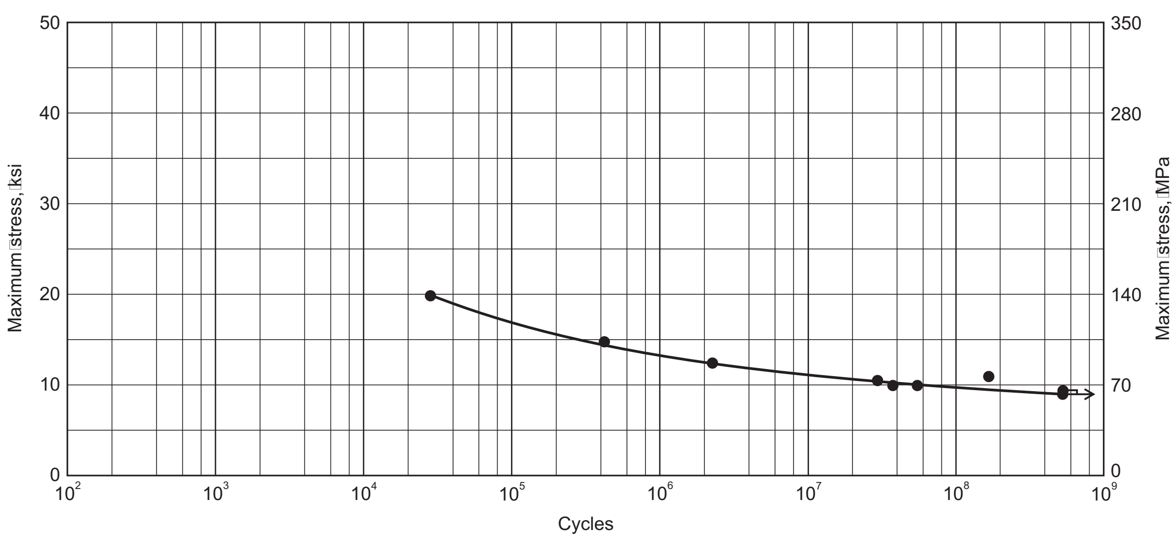

Fig. D6.15 242.0-T77, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

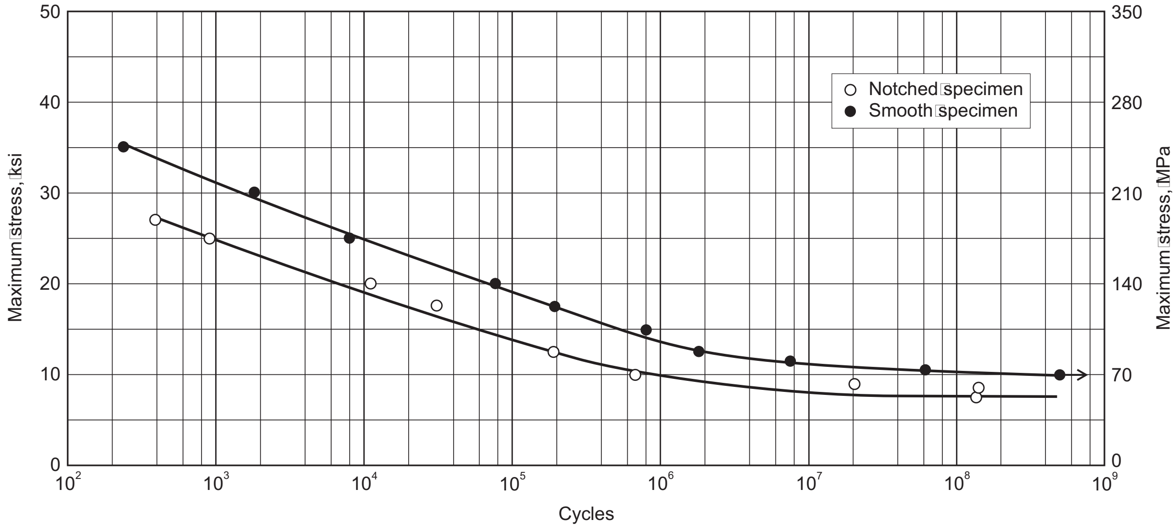

Fig. D6.16 242.0-T77, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

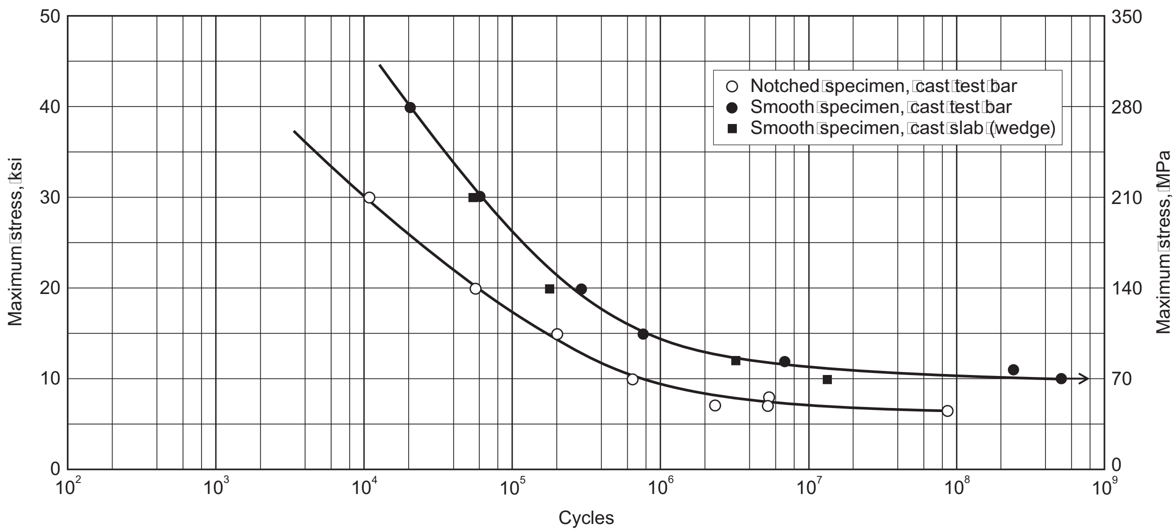

Fig. D6.17 249.0-T63, sand cast aluminum casting rotating-beam fatigue curve. Circles are smooth and notched specimens from one lot. Squares are smooth specimens taken from cast slab

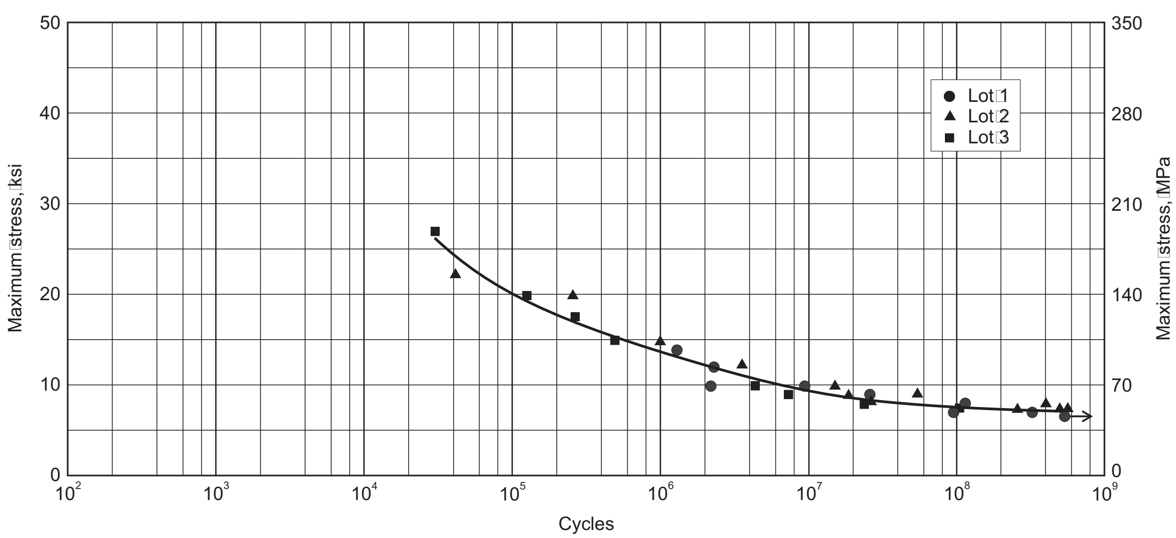

Fig. D6.18 295.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from three lots

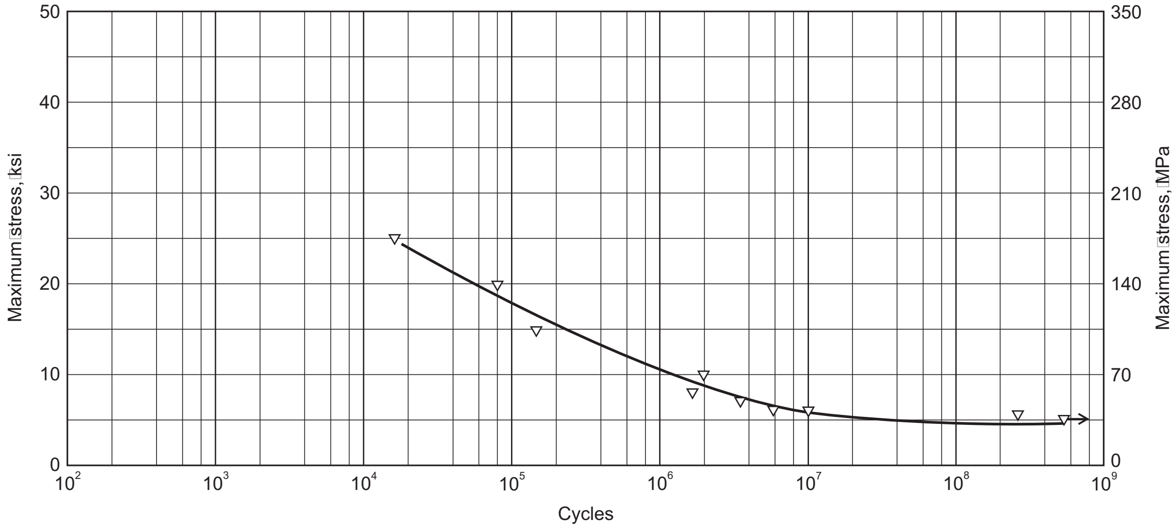

Fig. D6.19 295.0-T62, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from one lot

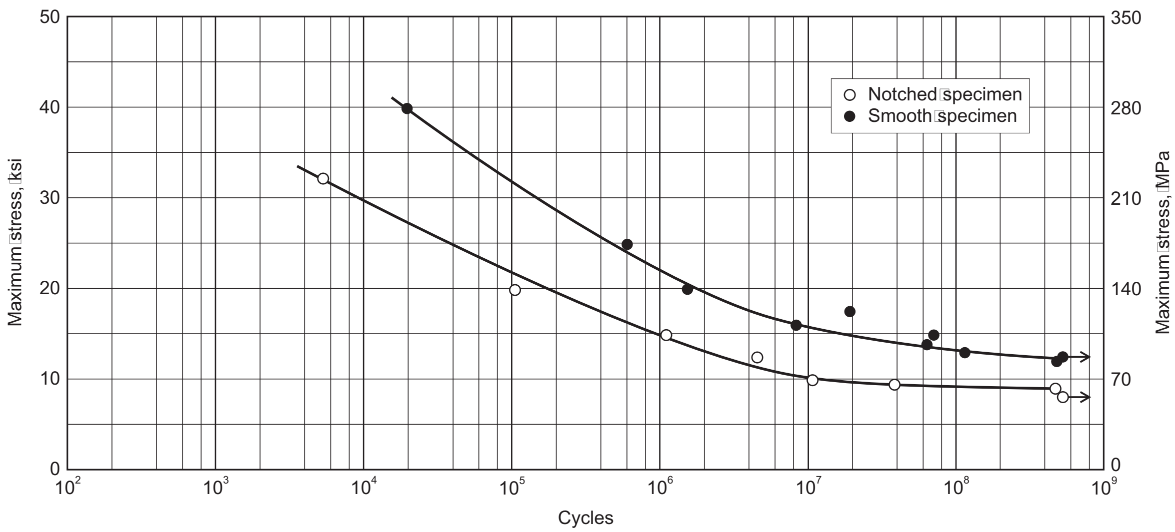

Fig. D6.20 296.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

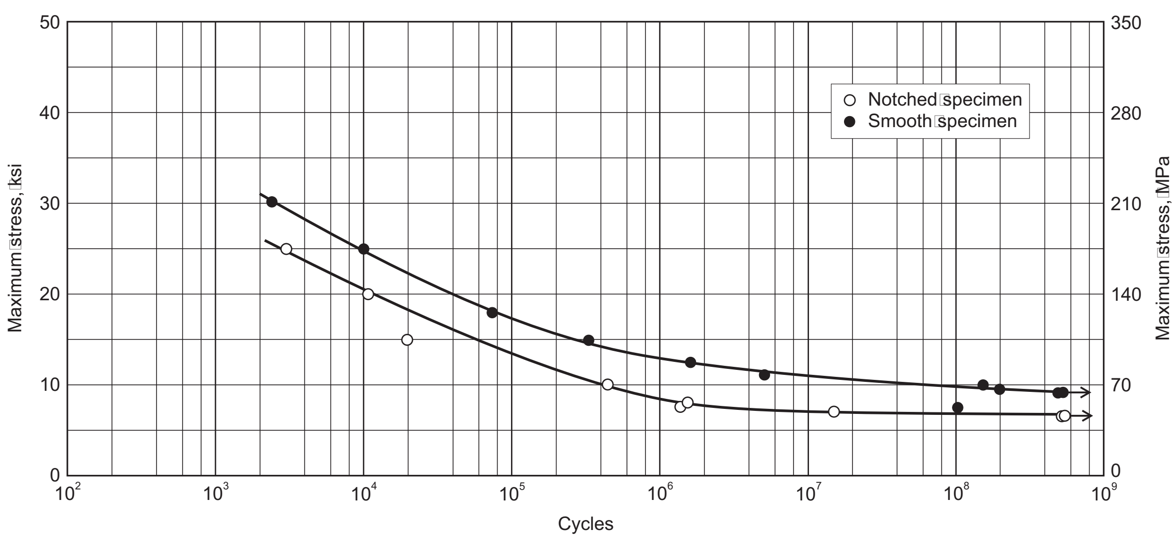

Fig. D6.21 296.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

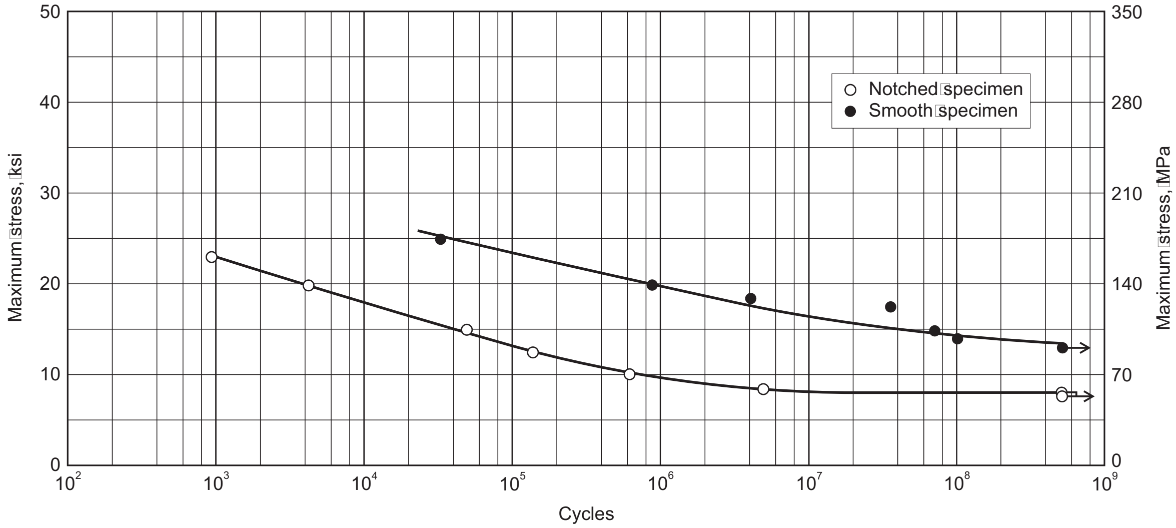

Fig. D6.22 308.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

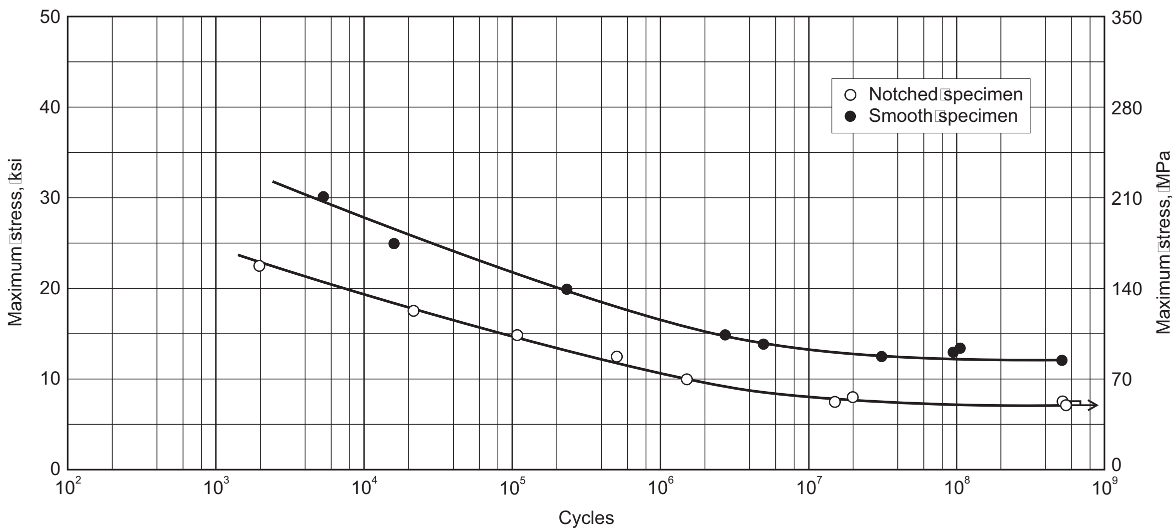

Fig. D6.23 308.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

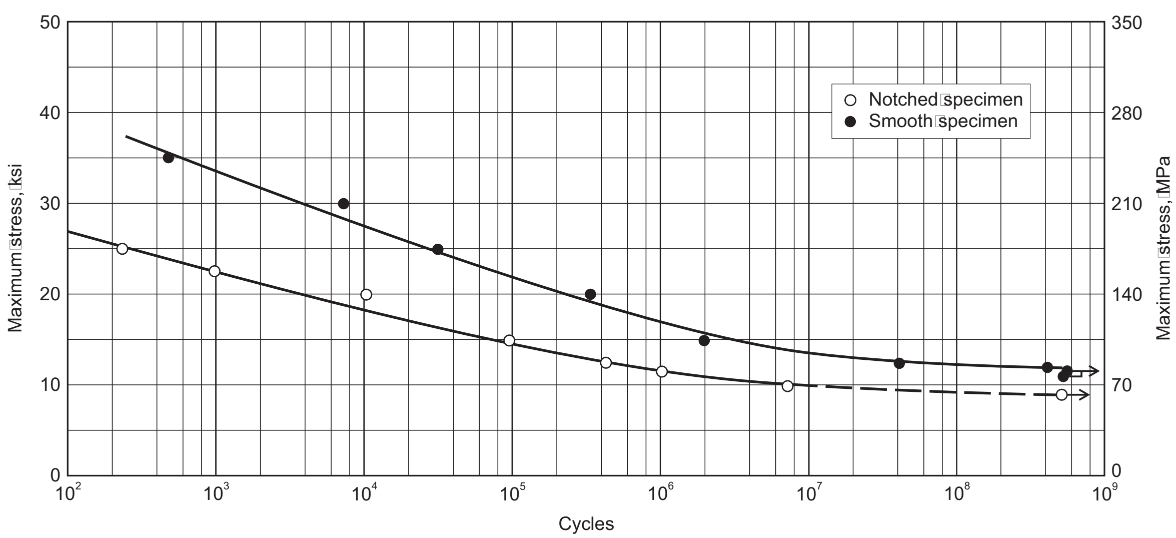

Fig. D6.24 319.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

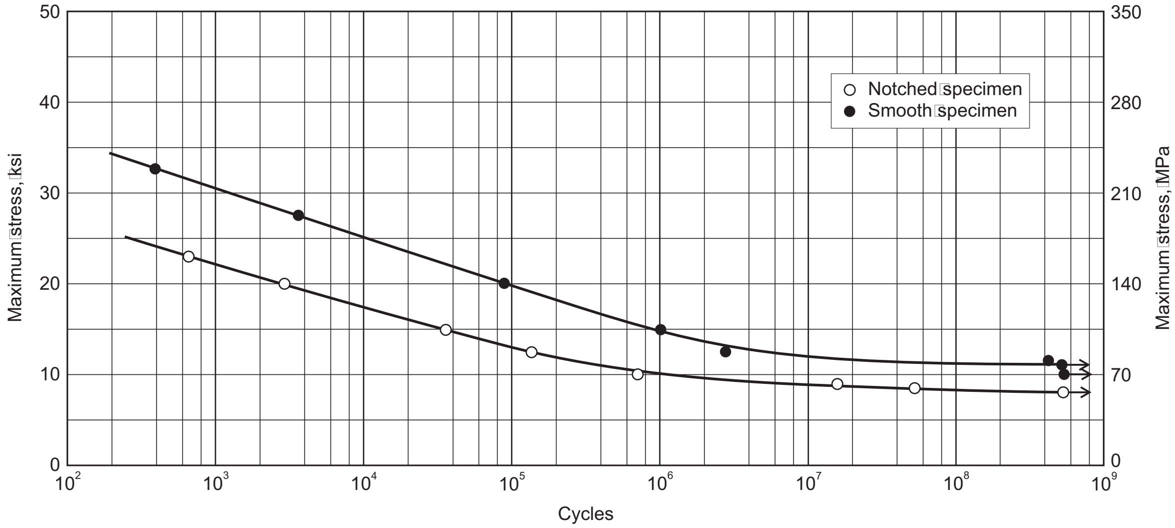

Fig. D6.25 319.0-T5, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

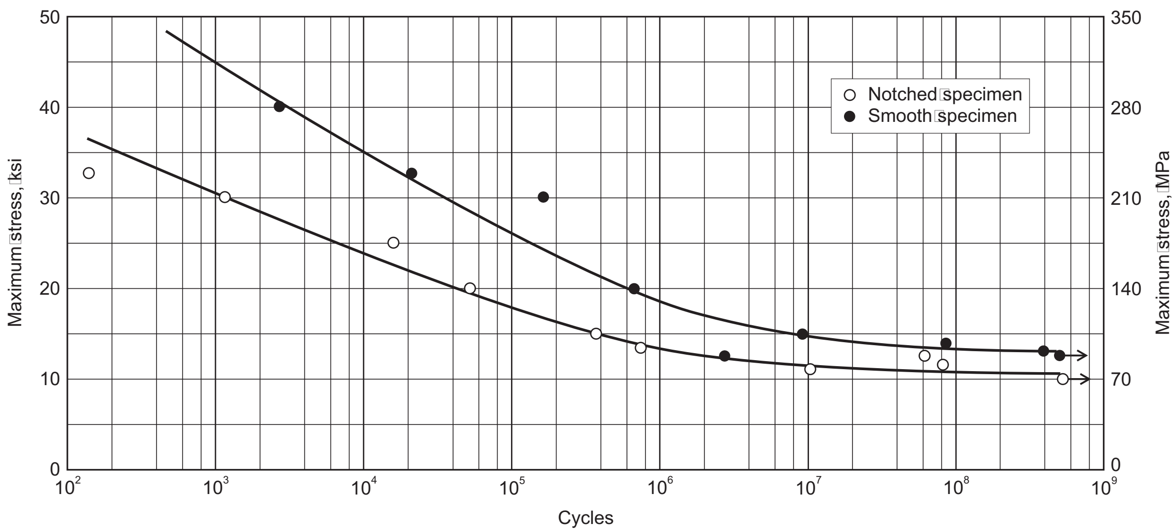

Fig. D6.26 319.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

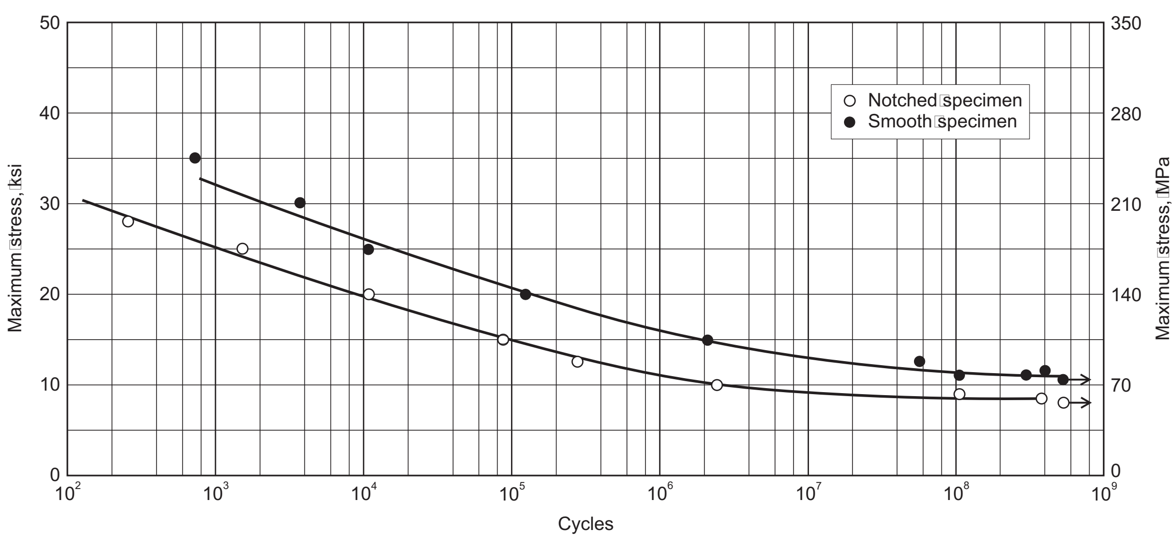

Fig. D6.27 319.0-T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

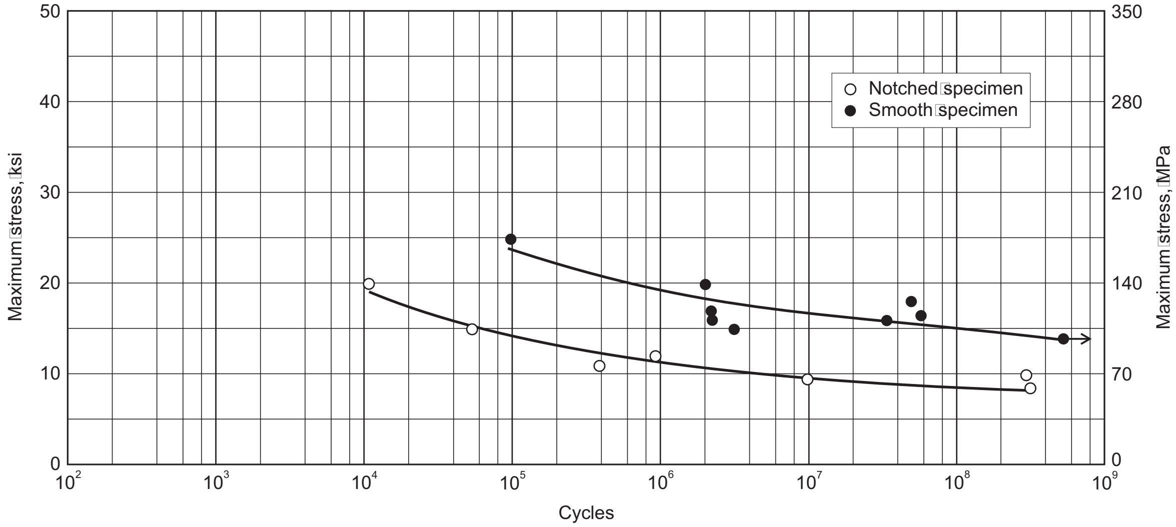

Fig. D6.28 332.0-T5, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

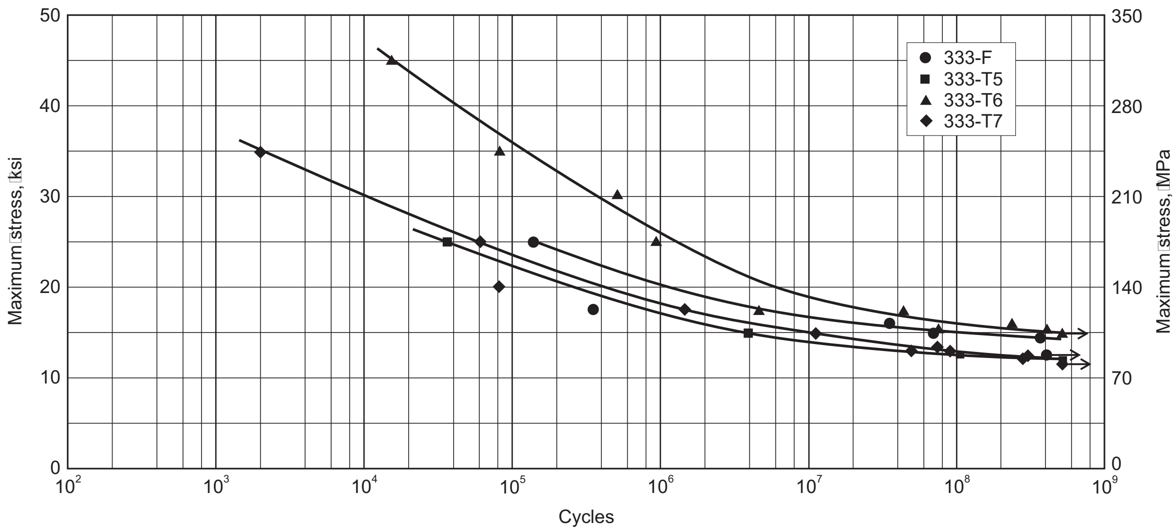

Fig. D6.29 333.0-F, -T5, -T6, and -T7, permanent mold aluminum casting rotating-beam fatigue curve. Comparison of smooth specimens as-cast (F) and with three heat treatments

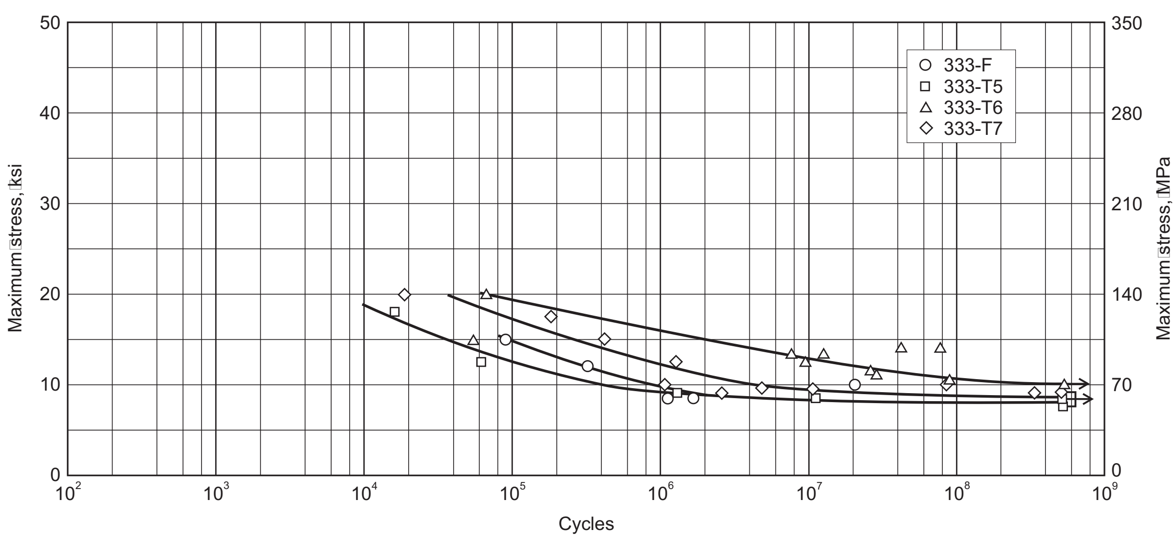

Fig. D6.30 333.0-F, -T5, -T6, and -T7, permanent mold aluminum casting rotating-beam fatigue curve. Comparison of notched specimens as-cast (F) and with three heat treatments

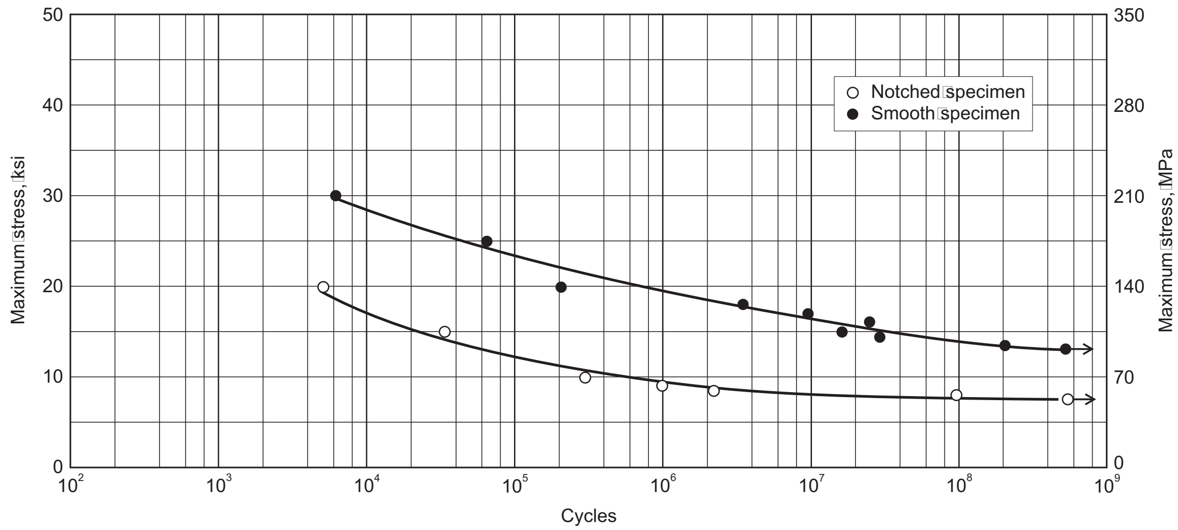

Fig. D6.31 333.0-T5, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

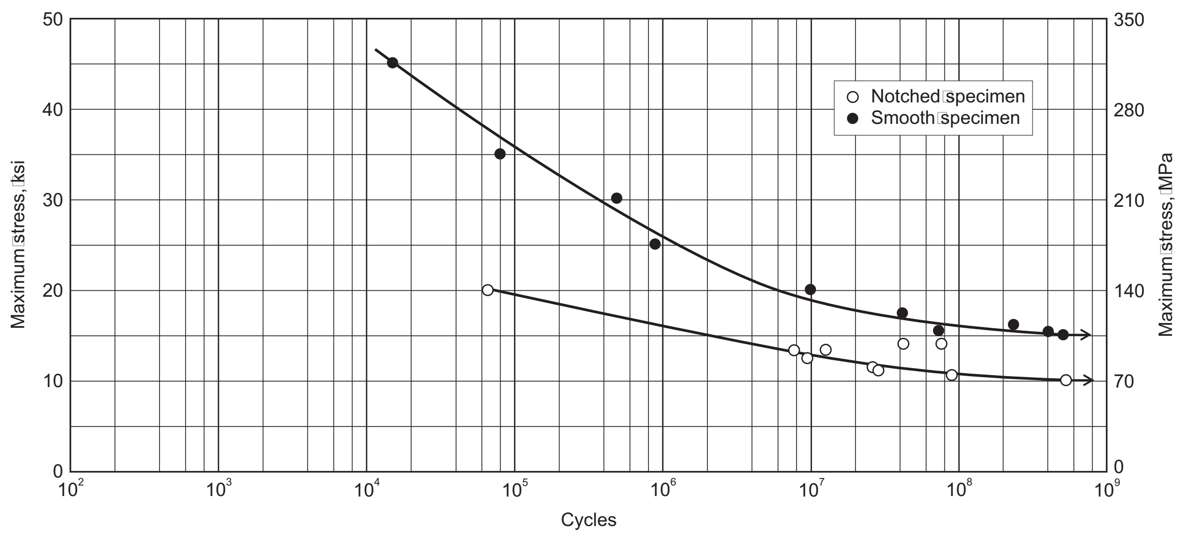

Fig. D6.32 333.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

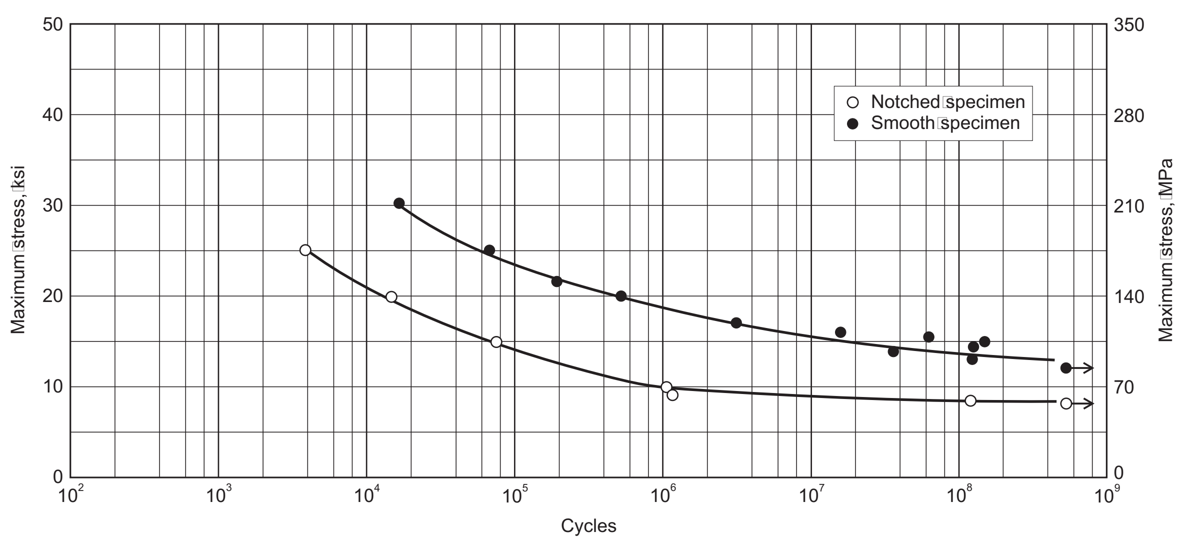

Fig. D6.33 333.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

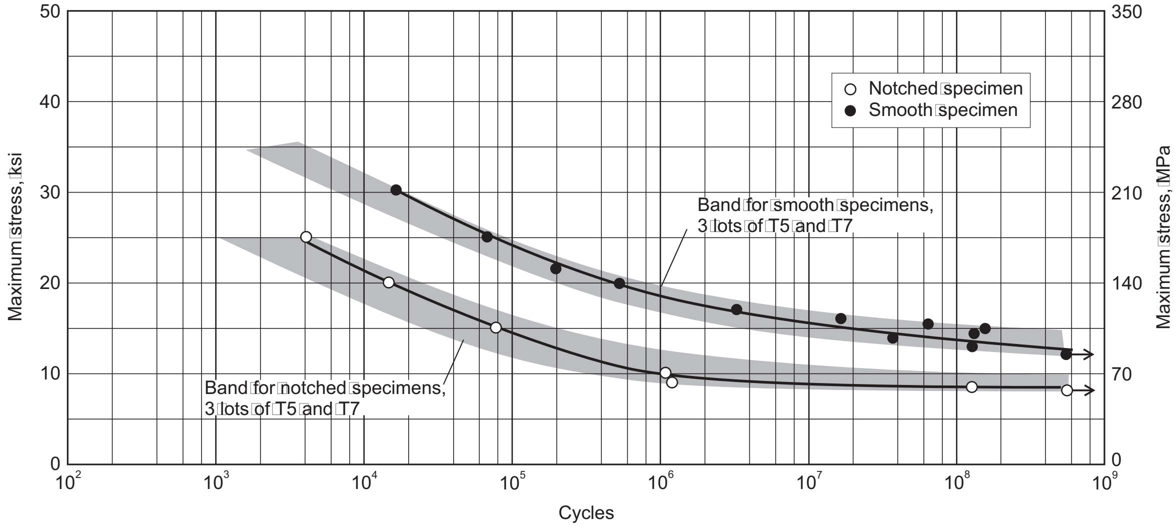

Fig. D6.34 333.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Data for smooth and notched specimens from one lot superimposed on bands of data from three lots of T5 and T7 data

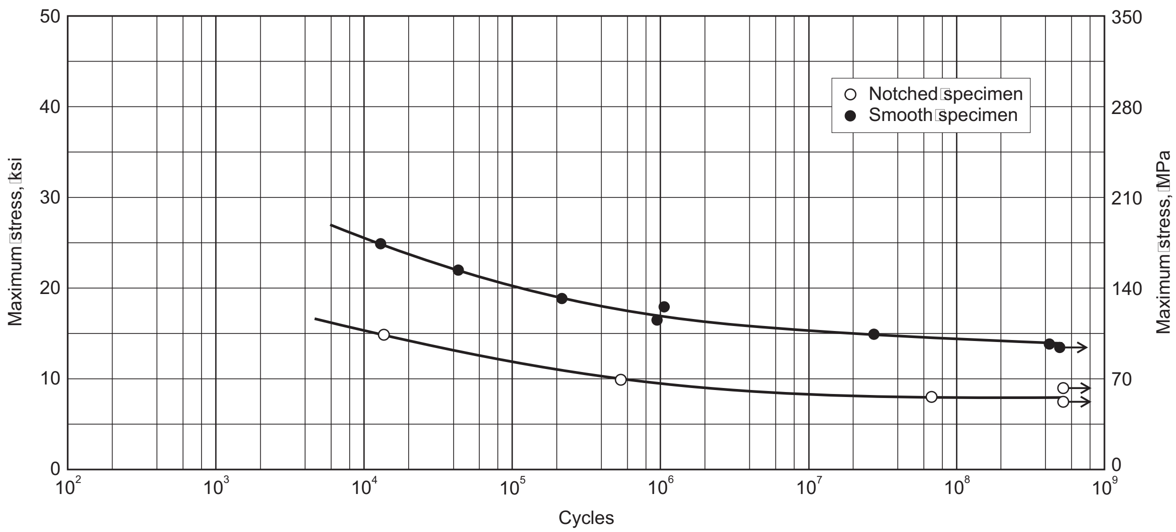

Fig. D6.35 336.0-T551, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

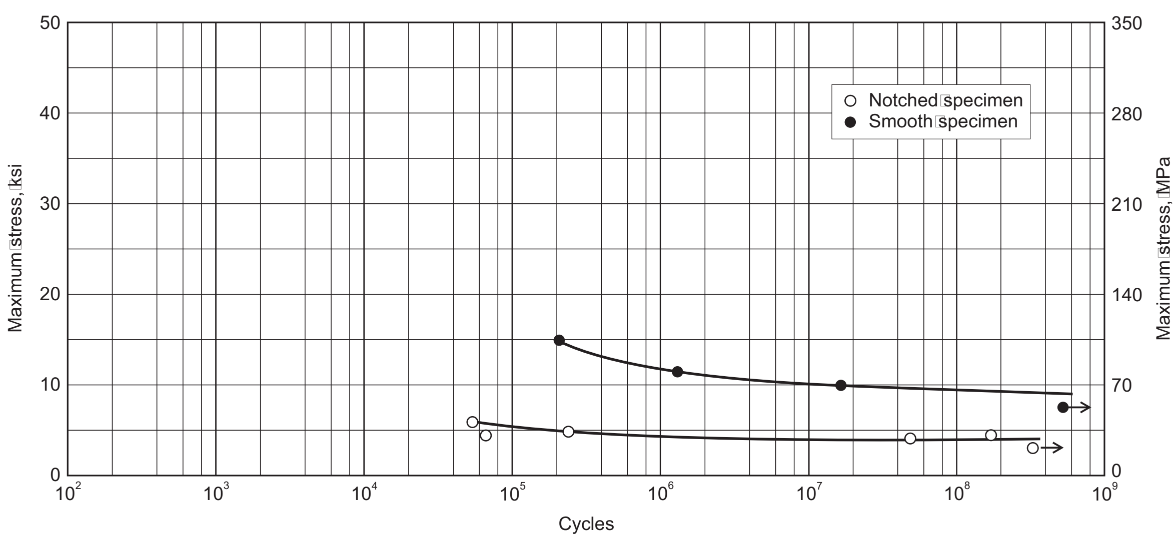

Fig. D6.36 A344.0-T4, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

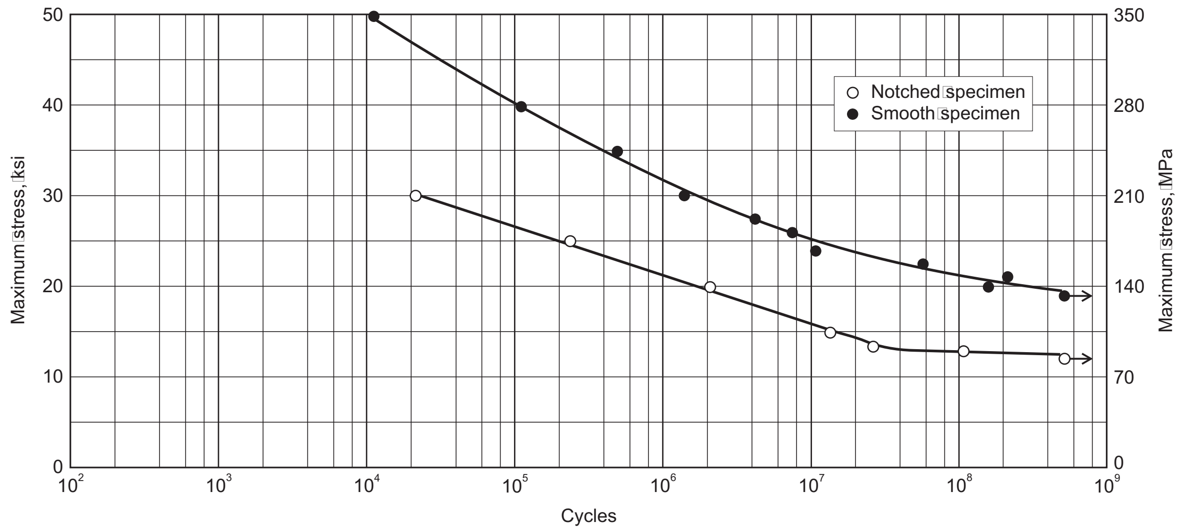

Fig. D6.37 354.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

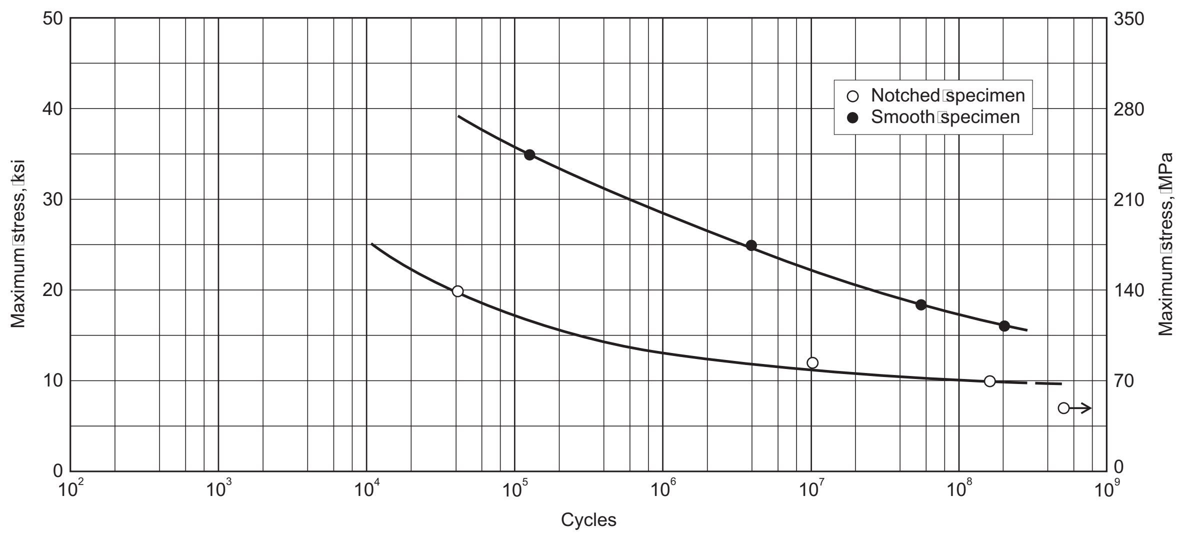

Fig. D6.38 354.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. Specimens were machined from cantilever beam cast test bars

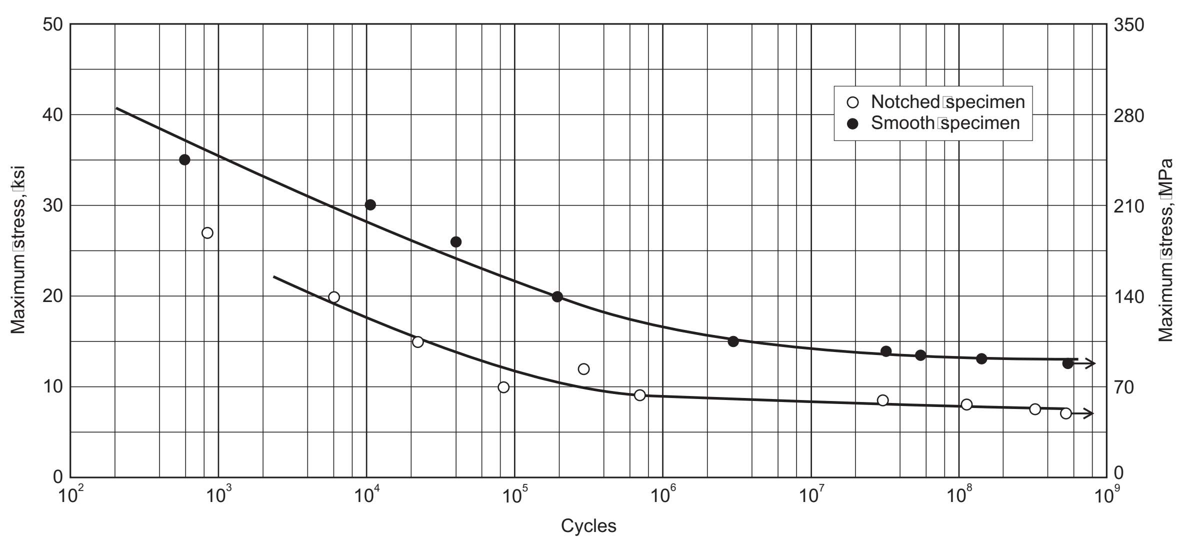

Fig. D6.39 355.0-T51, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

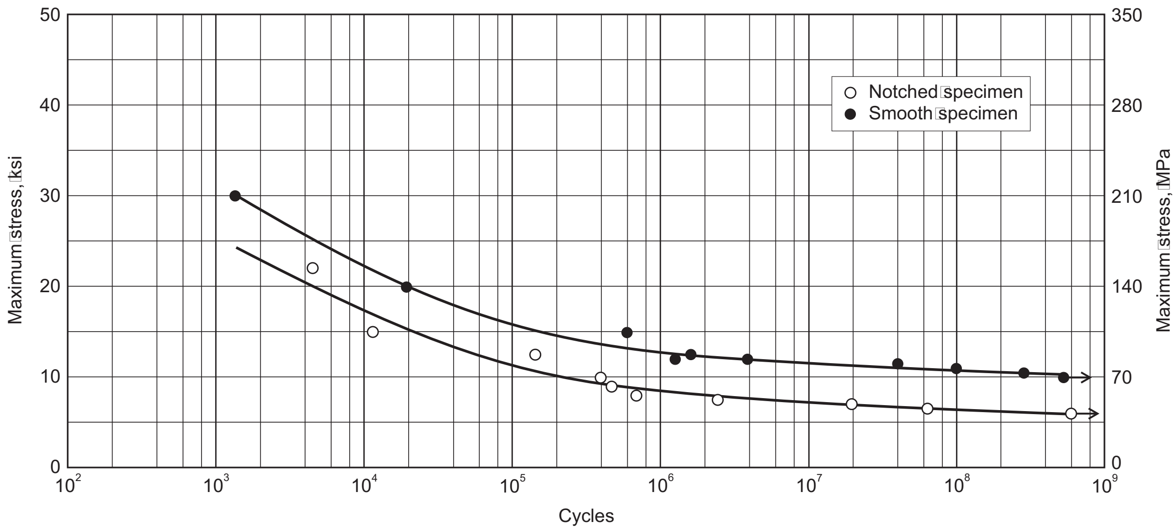

Fig. D6.40 355.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

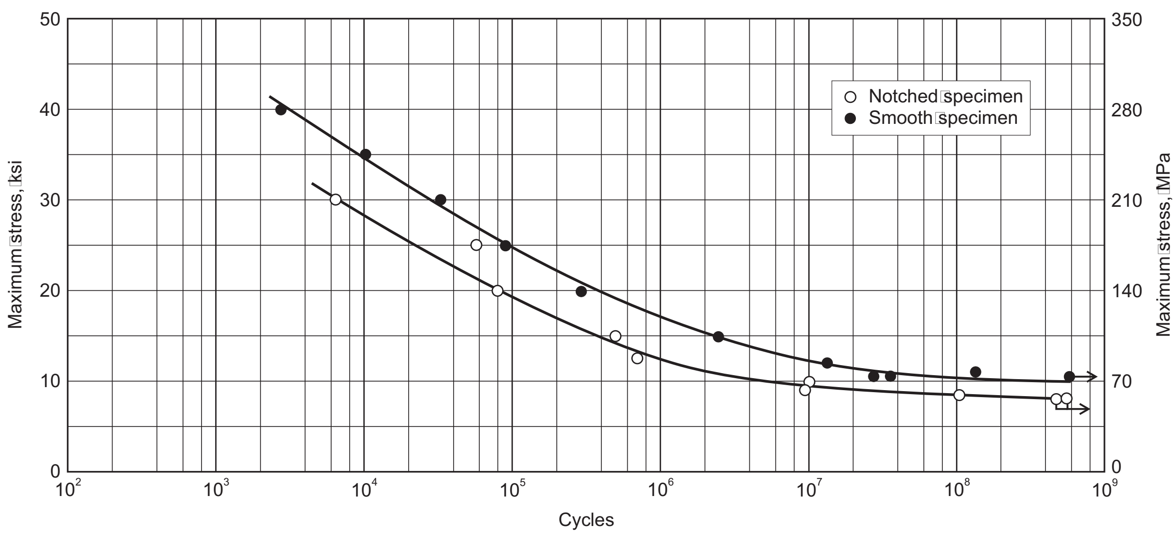

Fig. D6.41 355.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

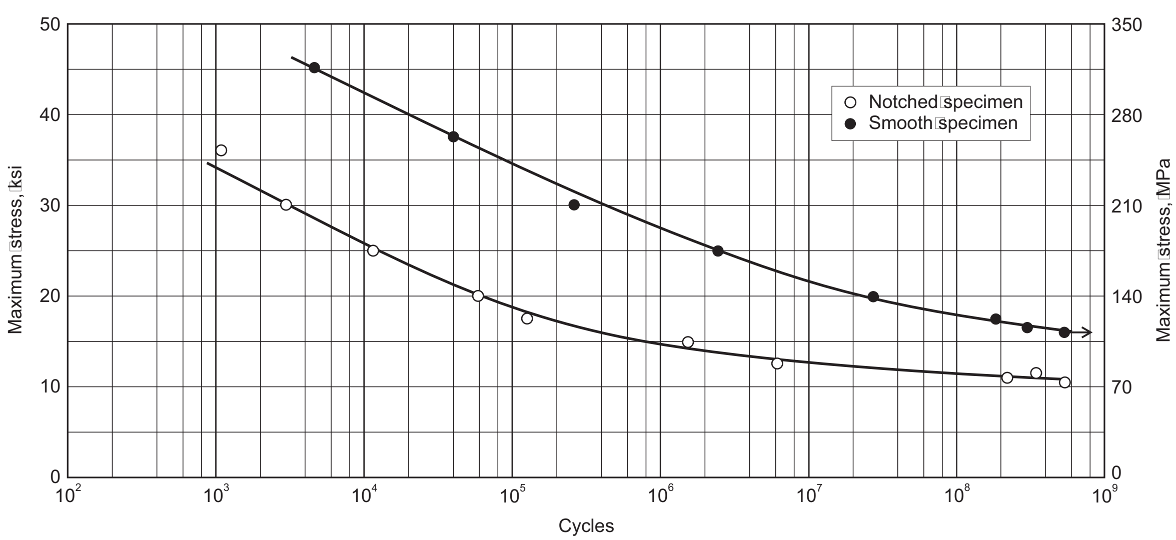

Fig. D6.42 355.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

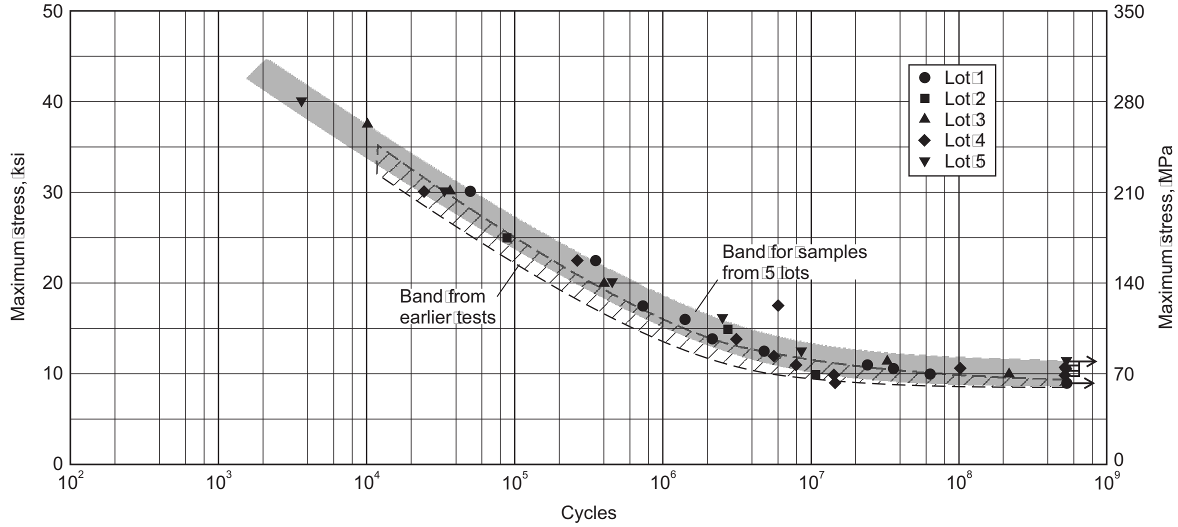

Fig. D6.43 355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from five lots. Band of these samples compared to band of samples from earlier tests

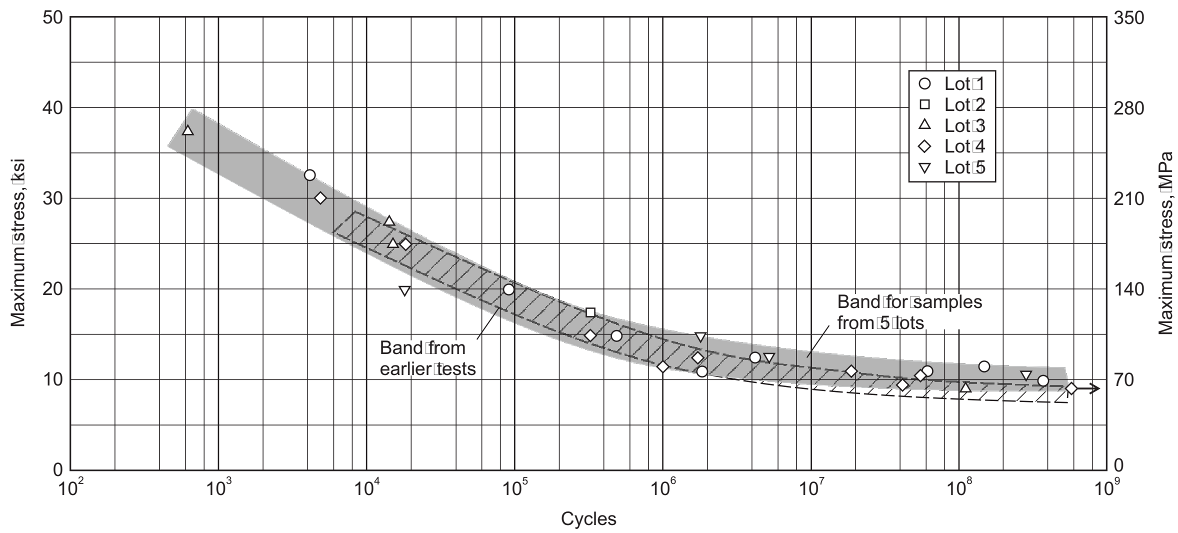

Fig. D6.44 355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from five lots. Band of these samples compared to band of samples from earlier tests

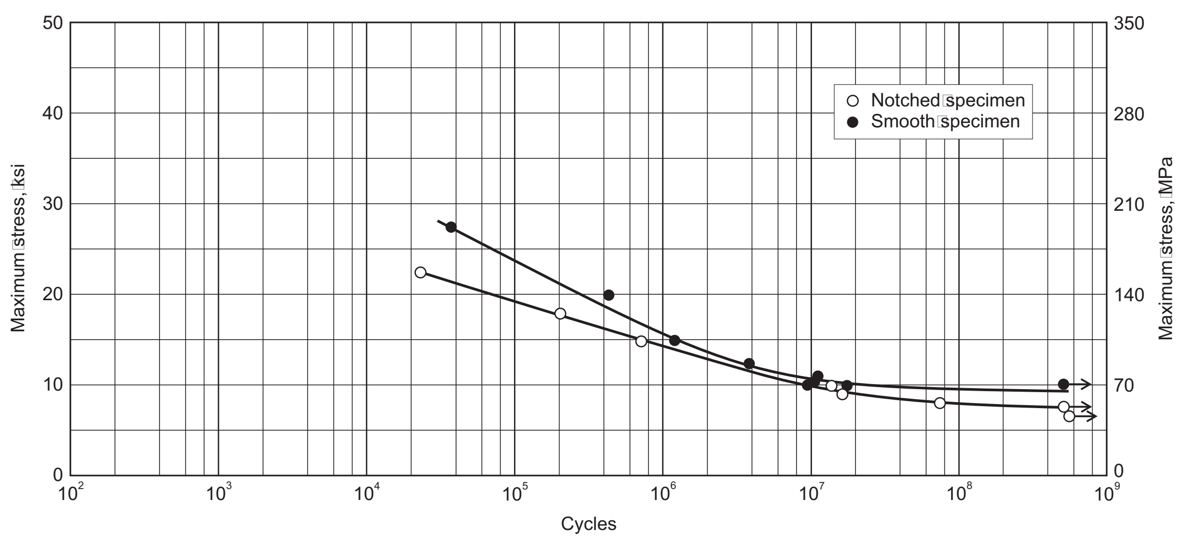

Fig. D6.45 355.0-T61, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

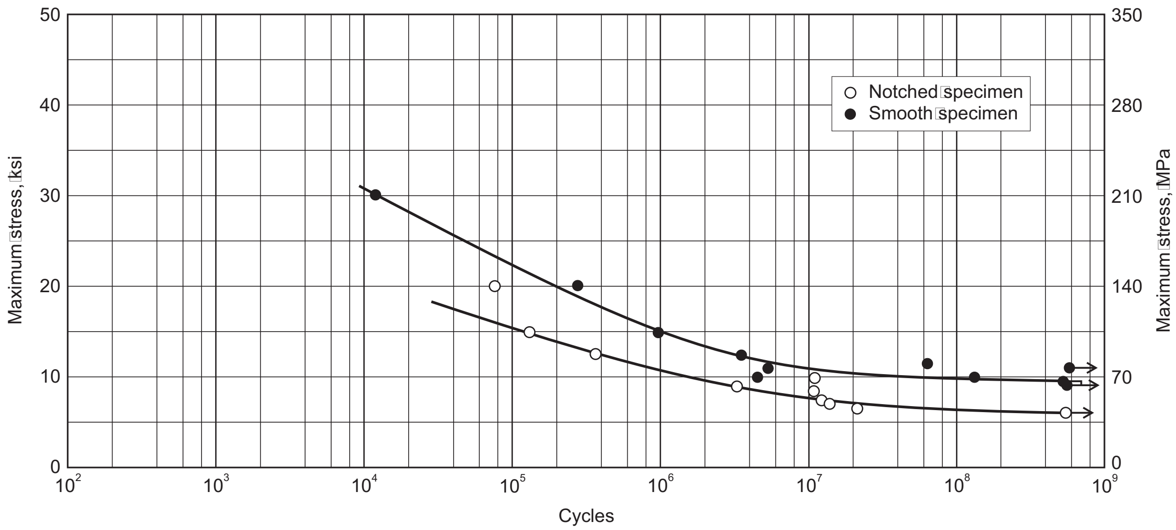

Fig. D6.46 355.0-T62, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

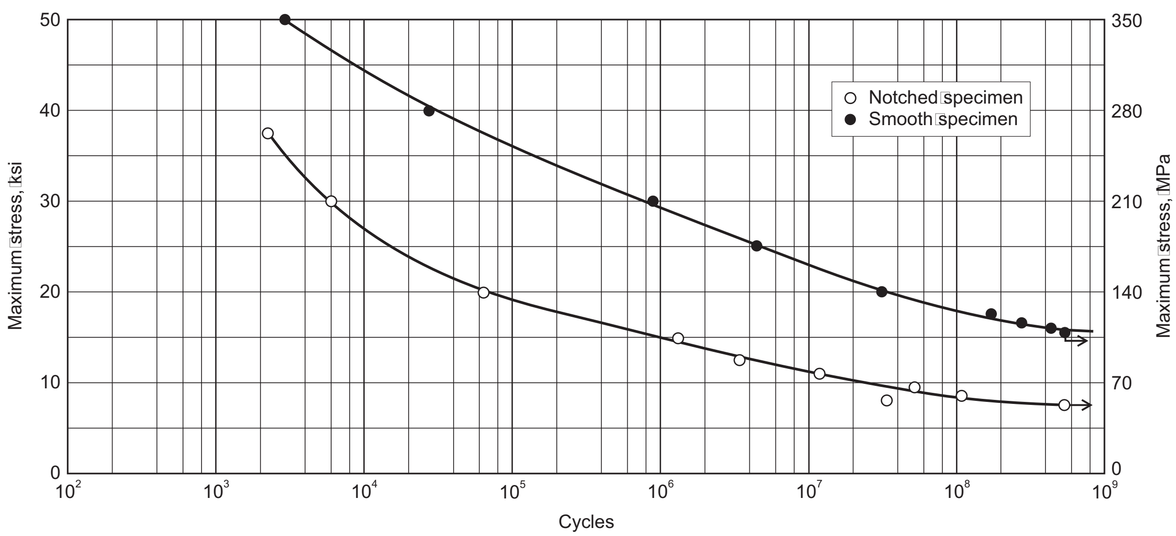

Fig. D6.47 355.0-T62, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

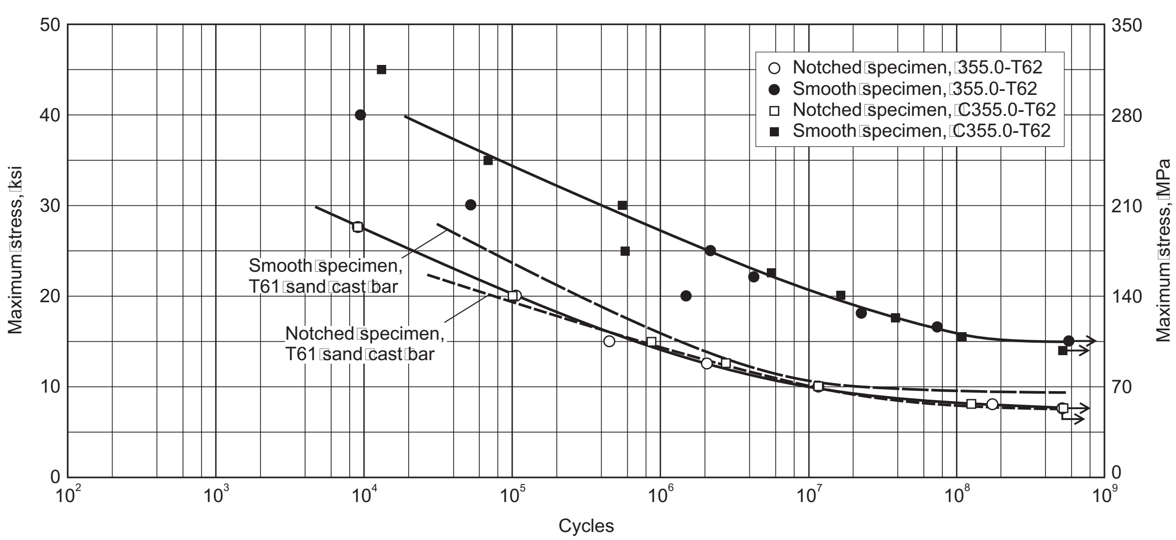

Fig. D6.48 355.0-T62, C355.0-T62, high-strength plaster cast aluminum casting rotating-beam fatigue curve. Comparison of smooth and notched specimen data for two lots. Broken lines are data for smooth and notched 355.0-T61 sand cast alloy.

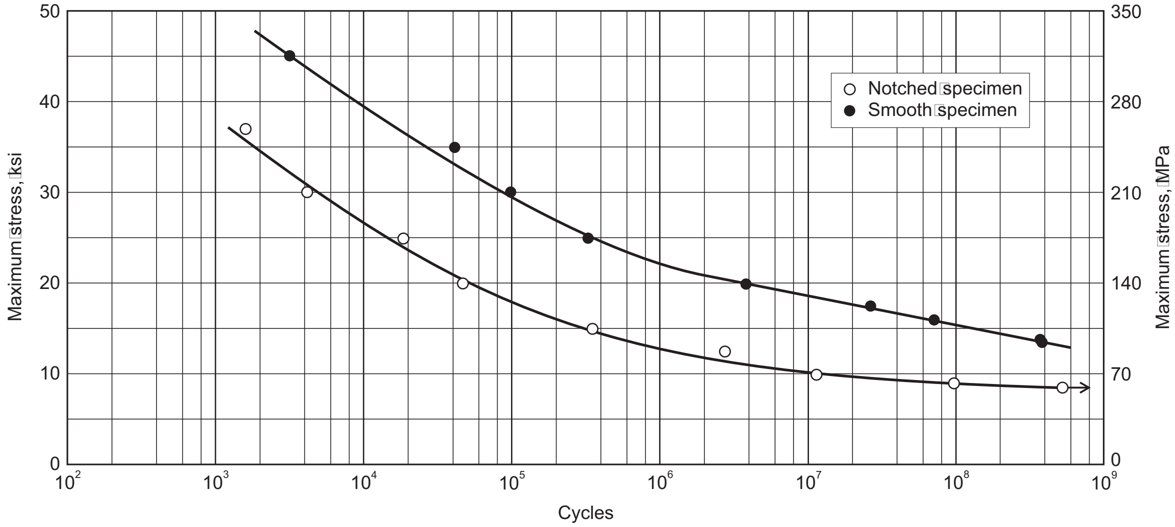

Fig. D6.49 355.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

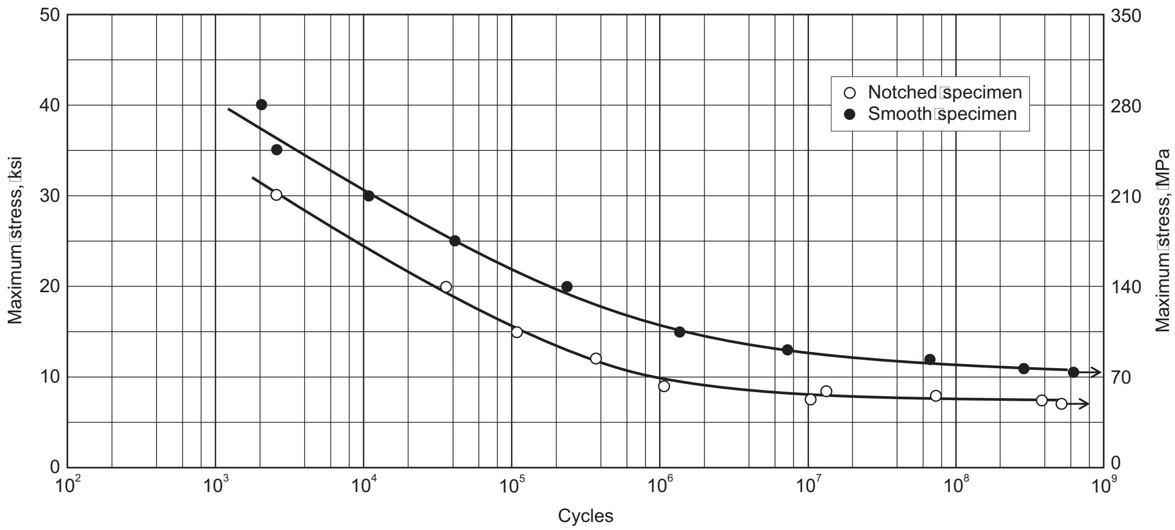

Fig. D6.50 355.0-T7, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

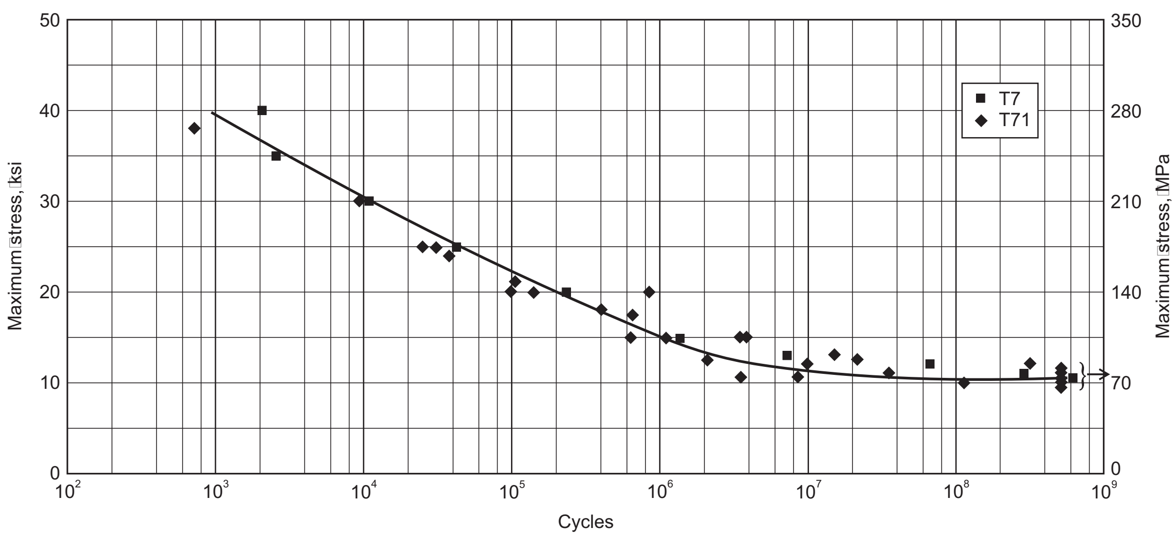

Fig. D6.51 355.0-T7, -T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens comparing effects of heat treatment

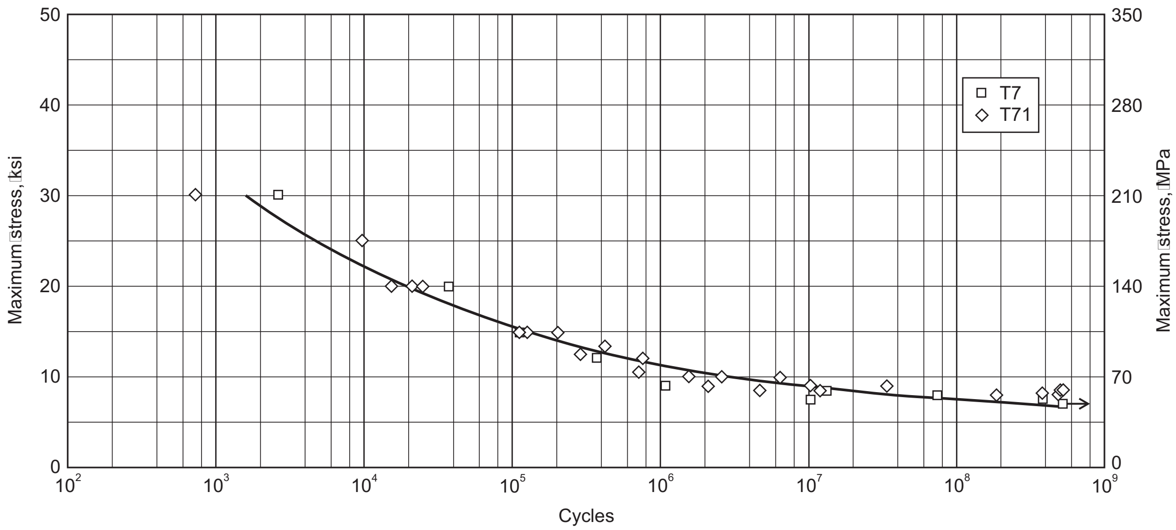

Fig. D6.52 355.0-T7, -T71, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens comparing effects of heat treatment

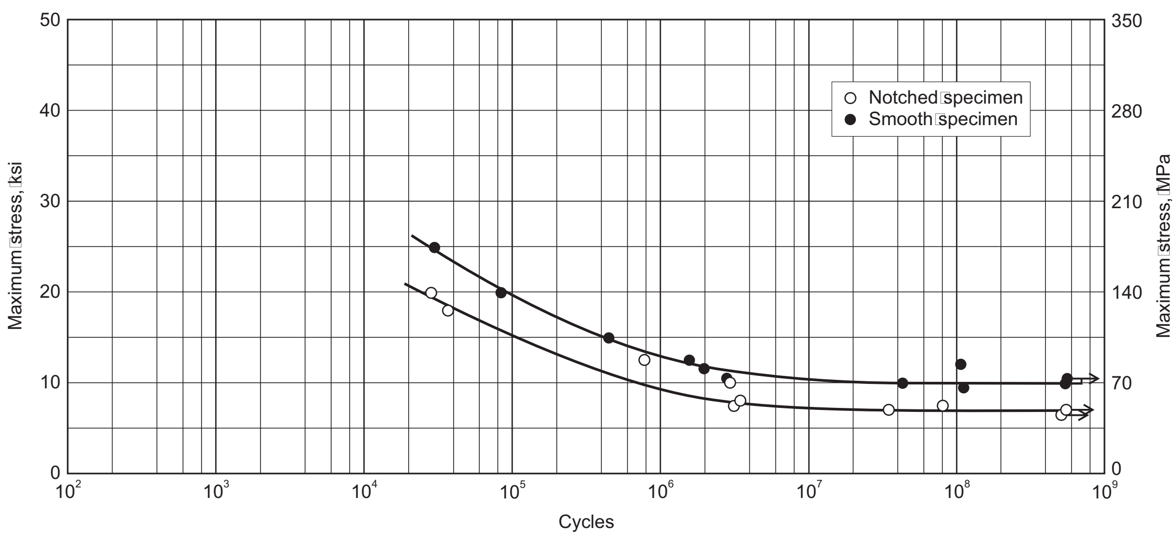

Fig. D6.53 355.0-T71, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

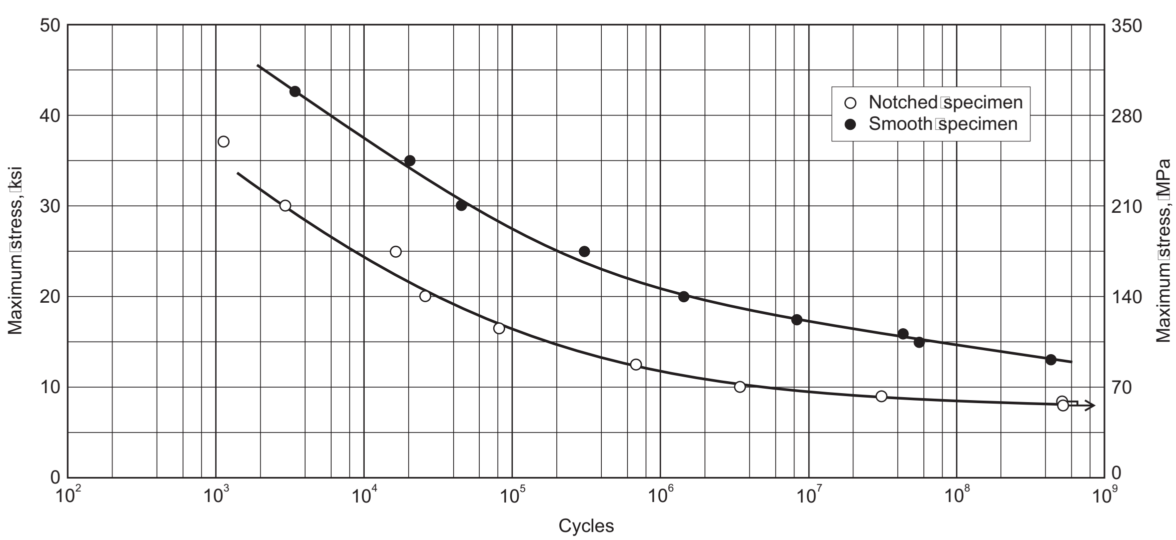

Fig. D6.54 355.0-T71, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

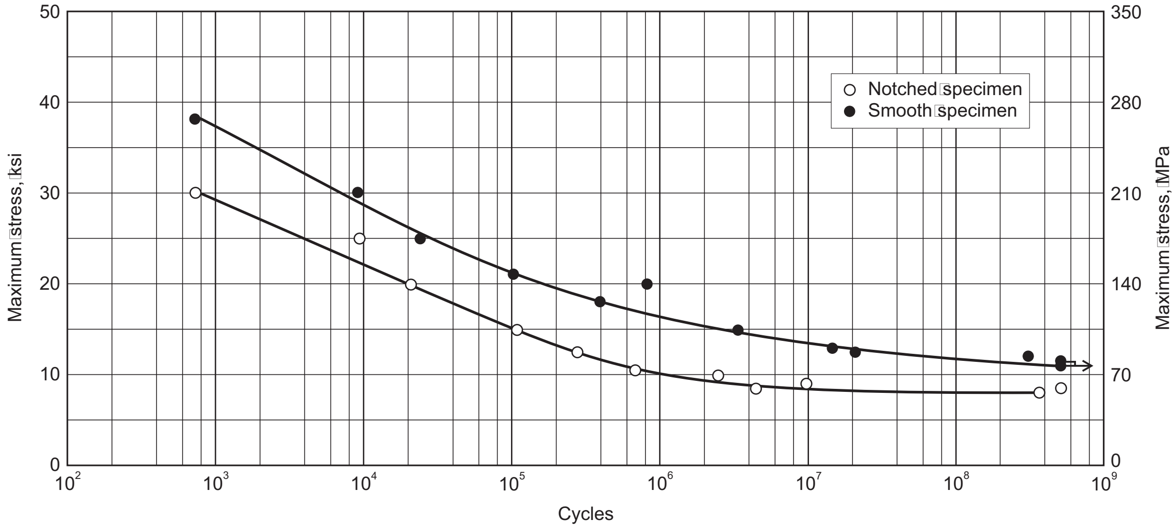

Fig. D6.55 355.0-T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

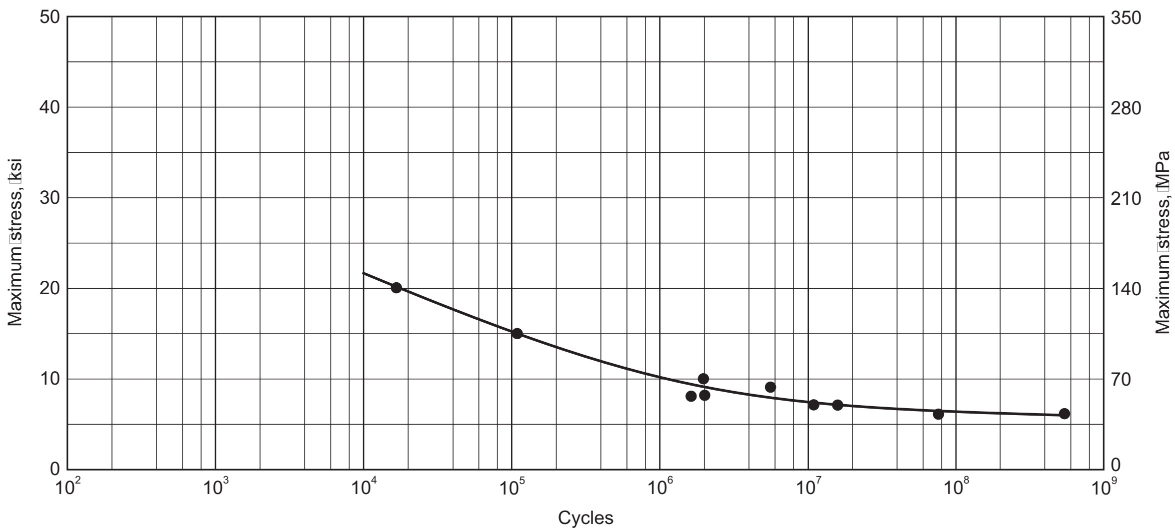

Fig. D6.56 355.0-T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimen from crankshaft casting, Fig. A3.3, Appendix 3

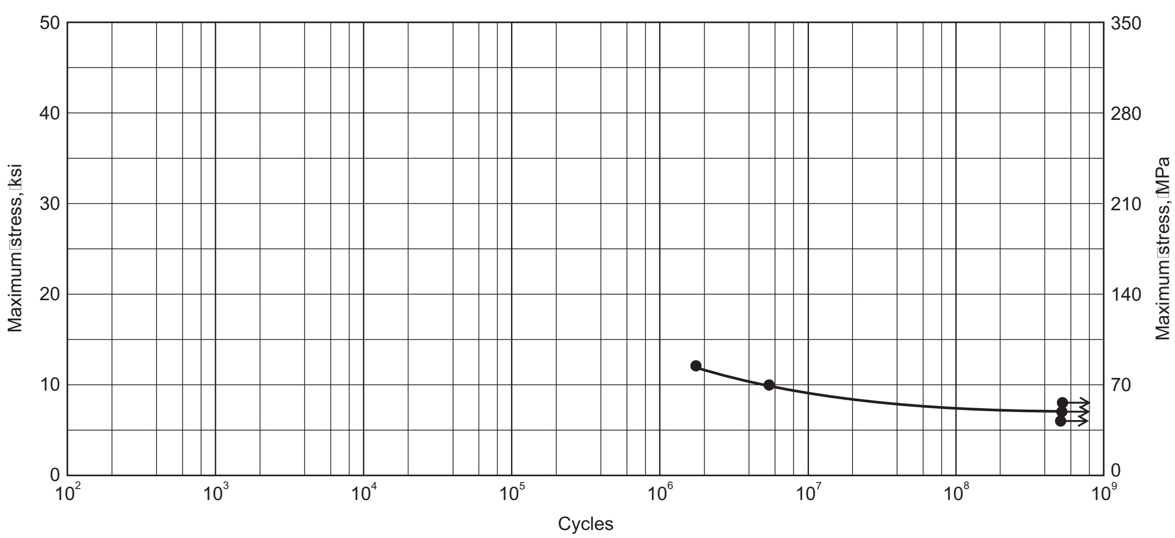

Fig. D6.57 A355.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Smooth, larger-than-standard specimens per Fig. A3.4, Appendix 3, from a single lot

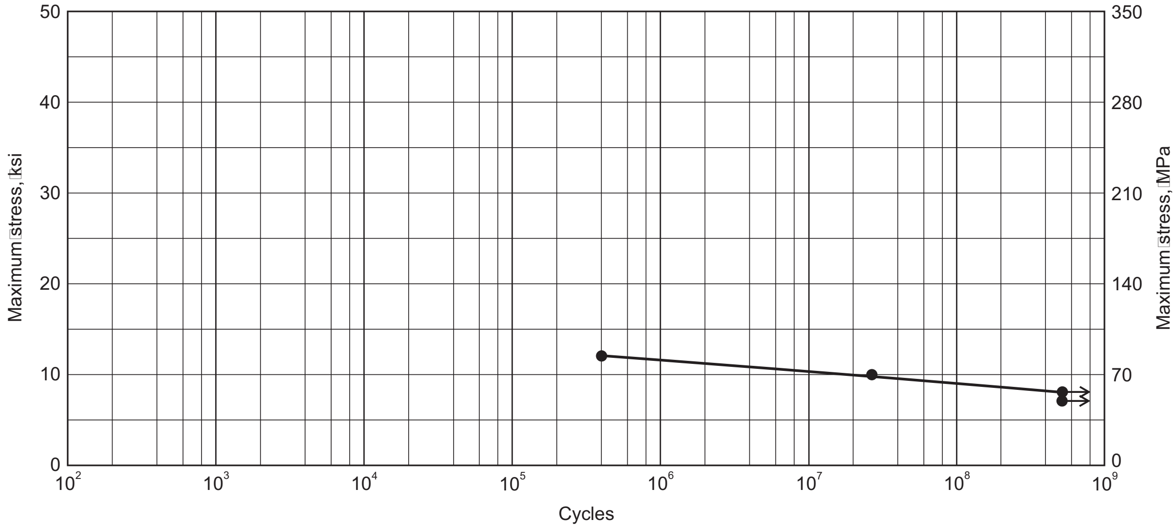

Fig. D6.58 A355.0-T59, sand cast aluminum casting rotating-beam fatigue curve. Smooth, larger-than-standard specimens per Fig. A3.4, Appendix 3, from a single lot

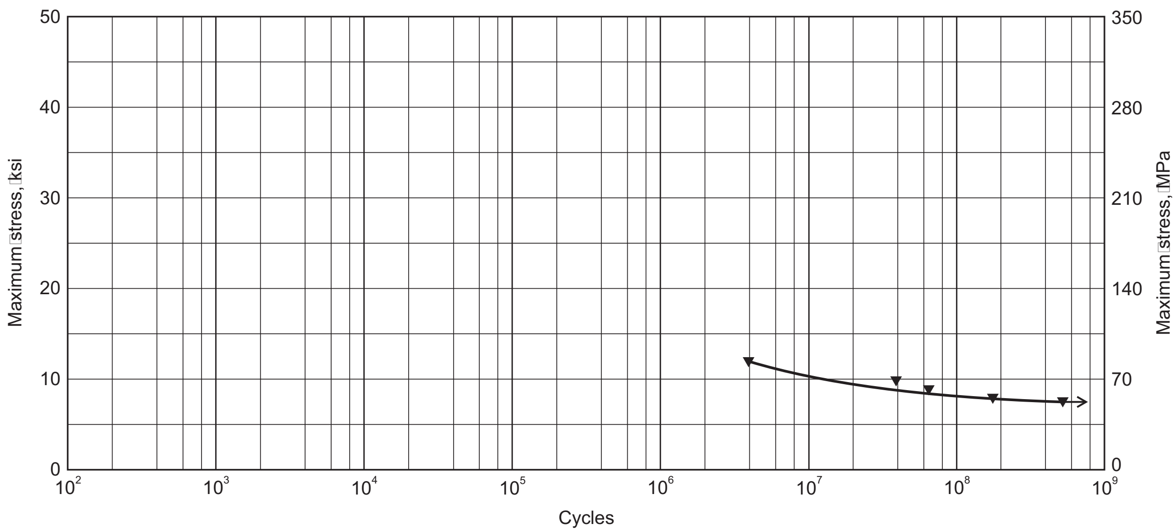

Fig. D6.59 A355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

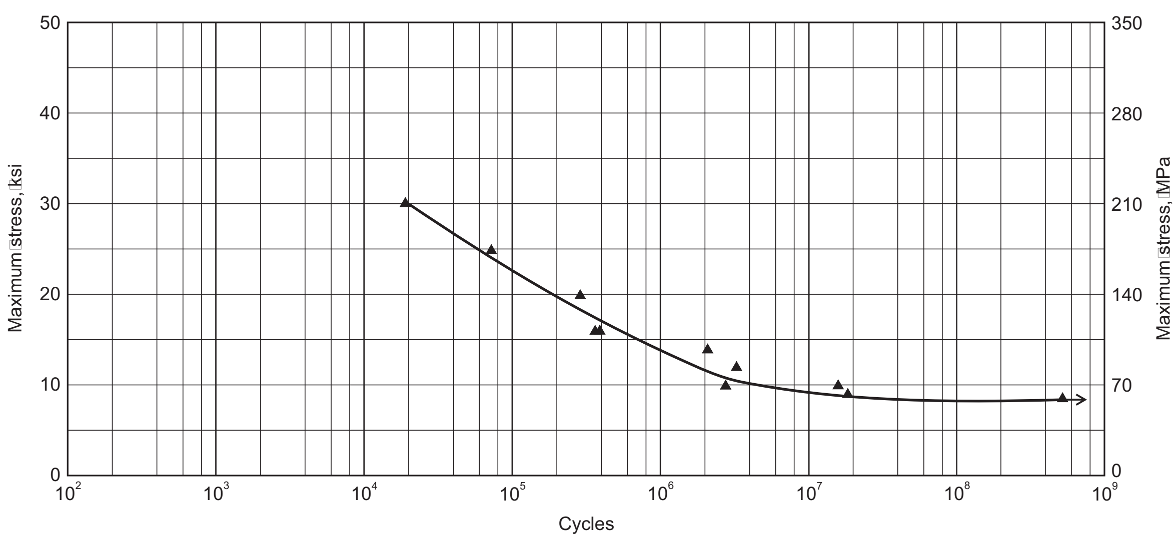

Fig. D6.60 B355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

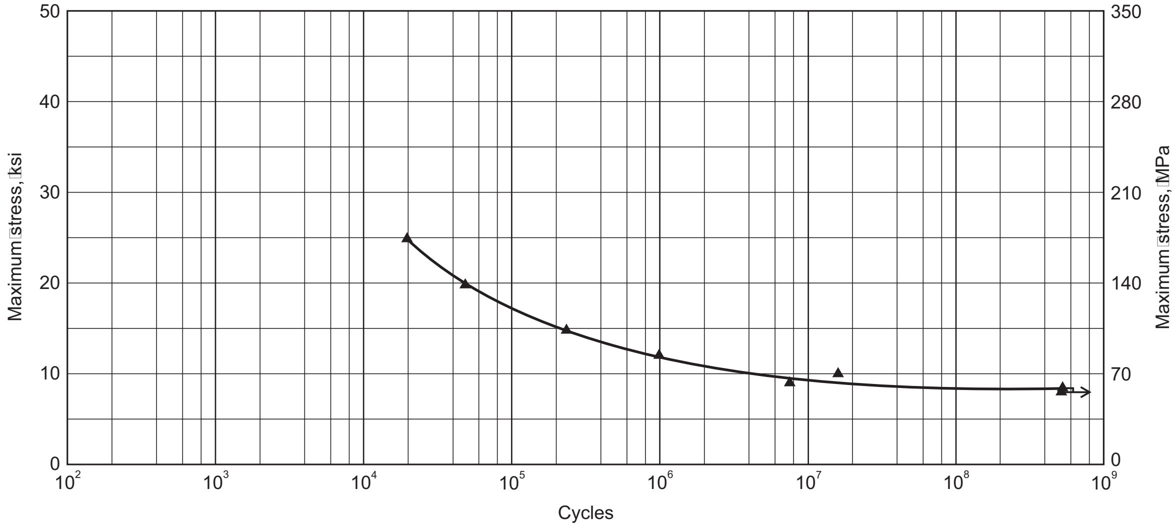

Fig. D6.61 B355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from one lot

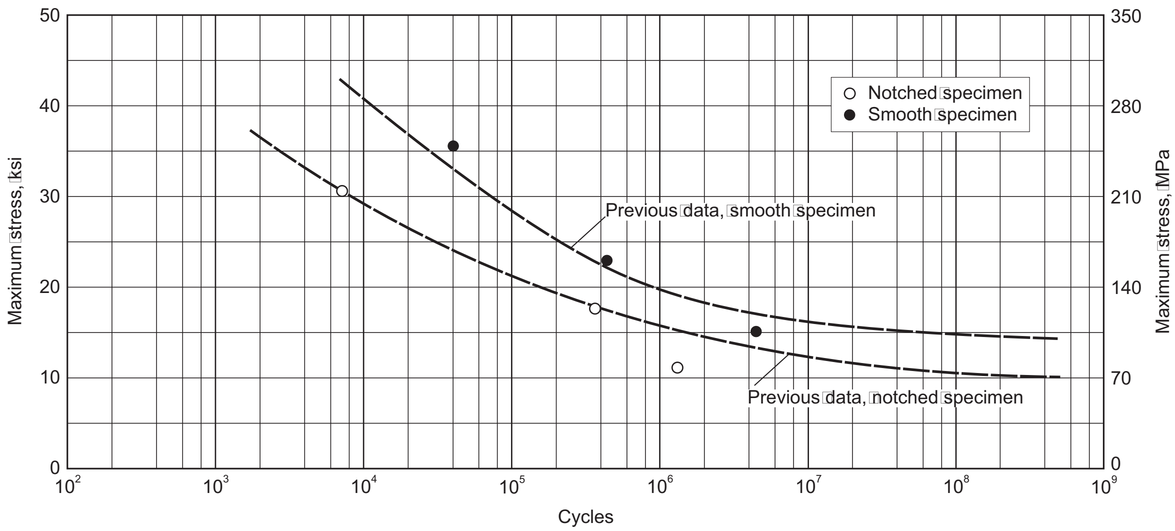

Fig. D6.62 C355.0-T61, high-strength plaster cast aluminum casting rotating-beam fatigue curve. Data from smooth and notched specimens of one lot compared to prior curves of C355.0-T61 permanent mold specimens

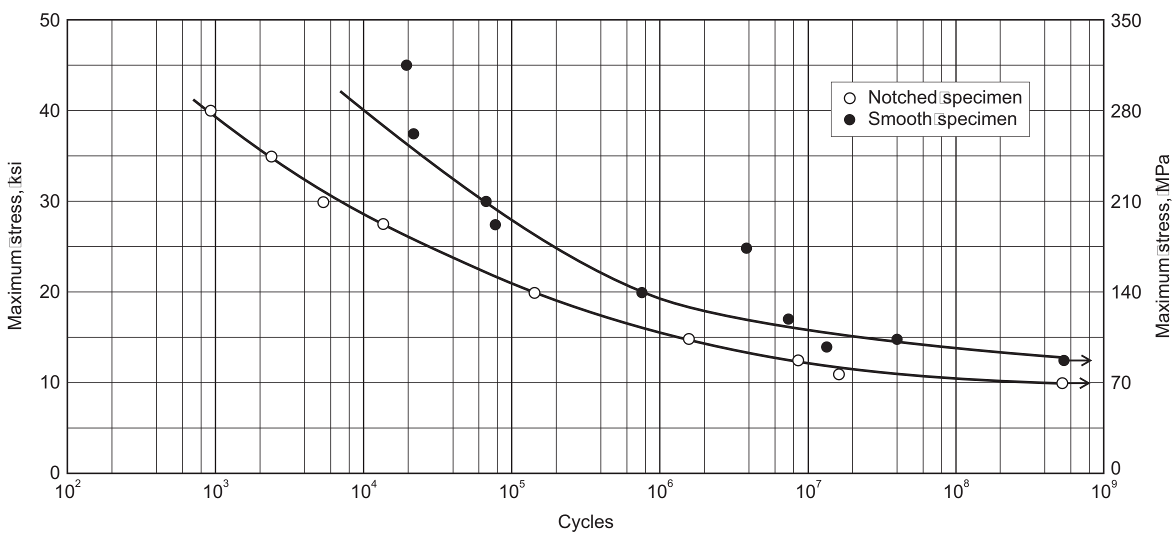

Fig. D6.63 C355.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. These data used for comparison in Fig. D6.62.

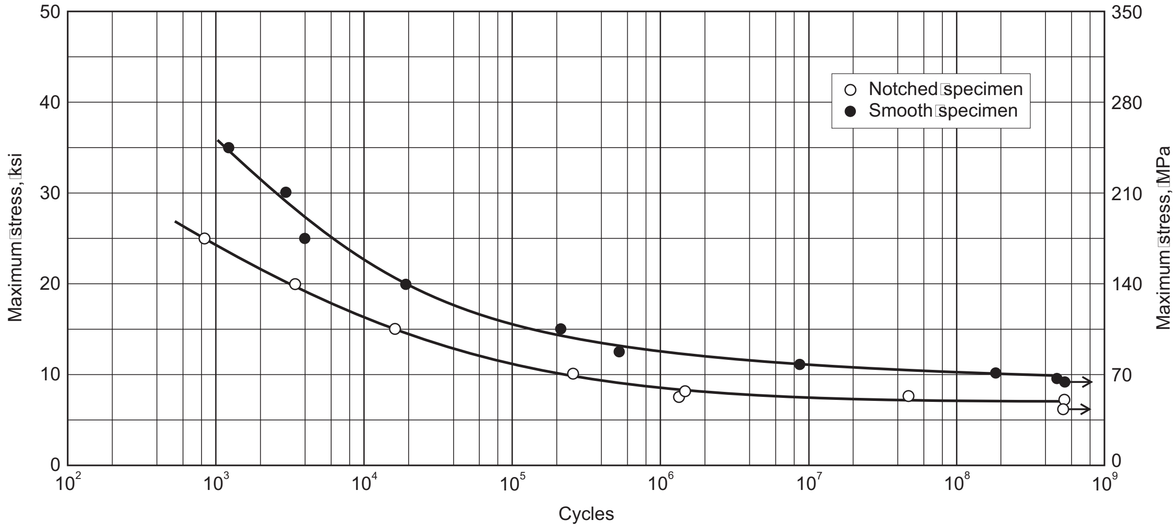

Fig. D6.64 356.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

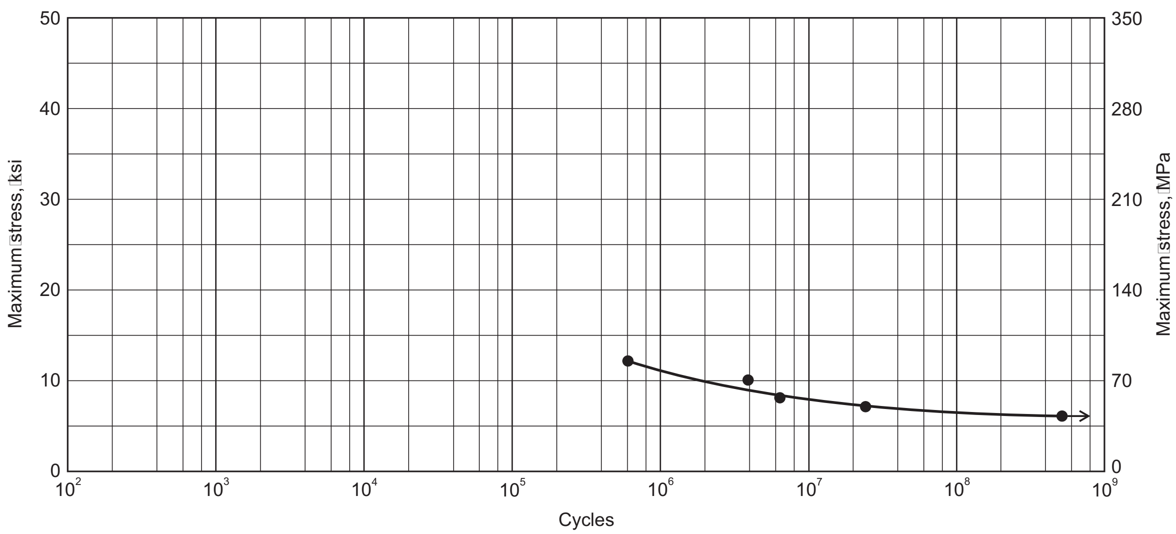

Fig. D6.65 356.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Smooth larger than standard specimens per Fig. A3.4, Appendix 3, from a single lot

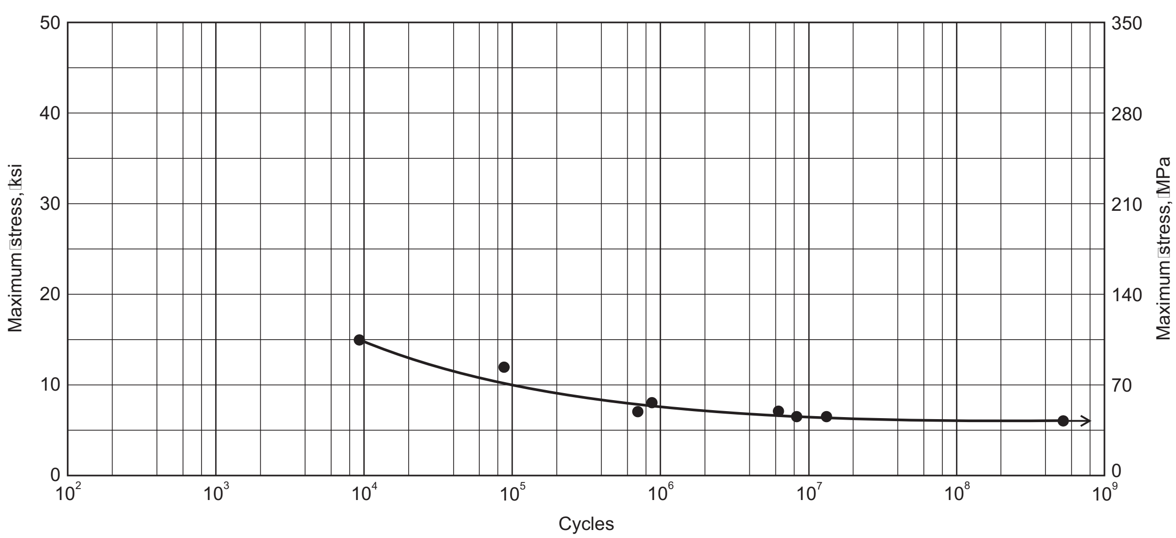

Fig. D6.66 356.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from one lot

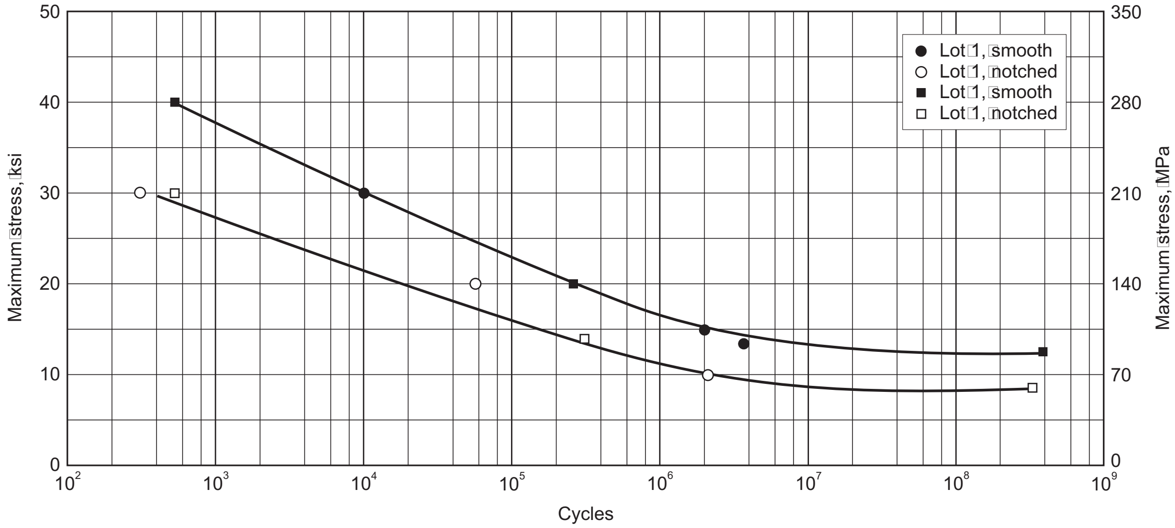

Fig. D6.67 356.0-T6, high-strength plaster cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from two lots

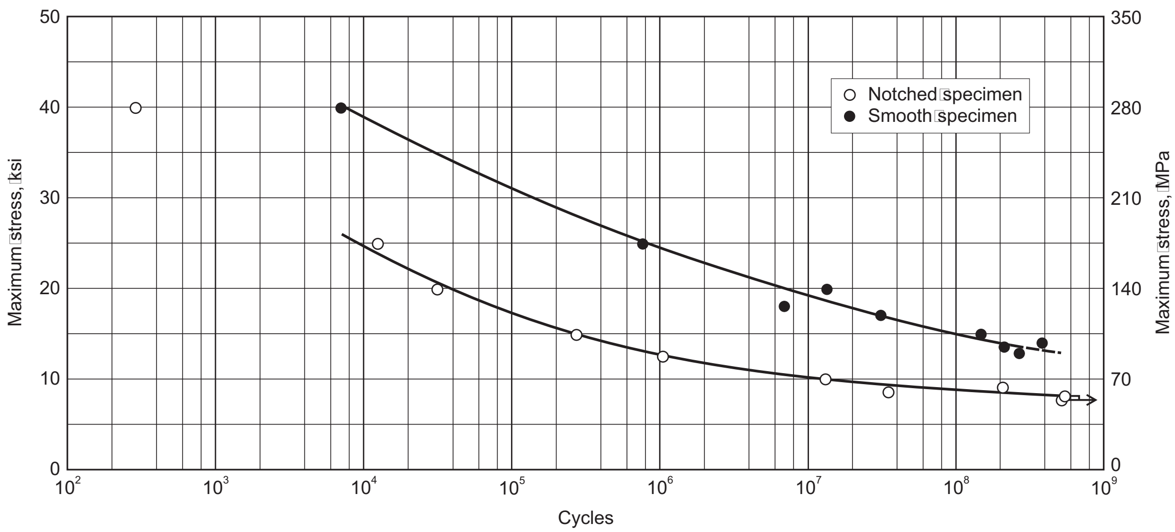

Fig. D6.68 356.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

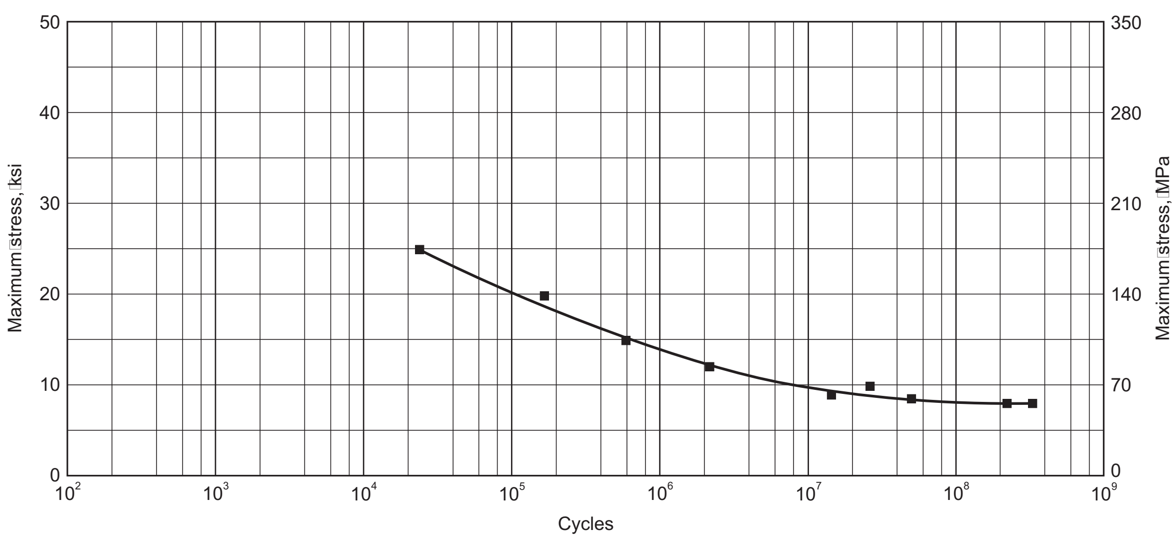

Fig. D6.69 356.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

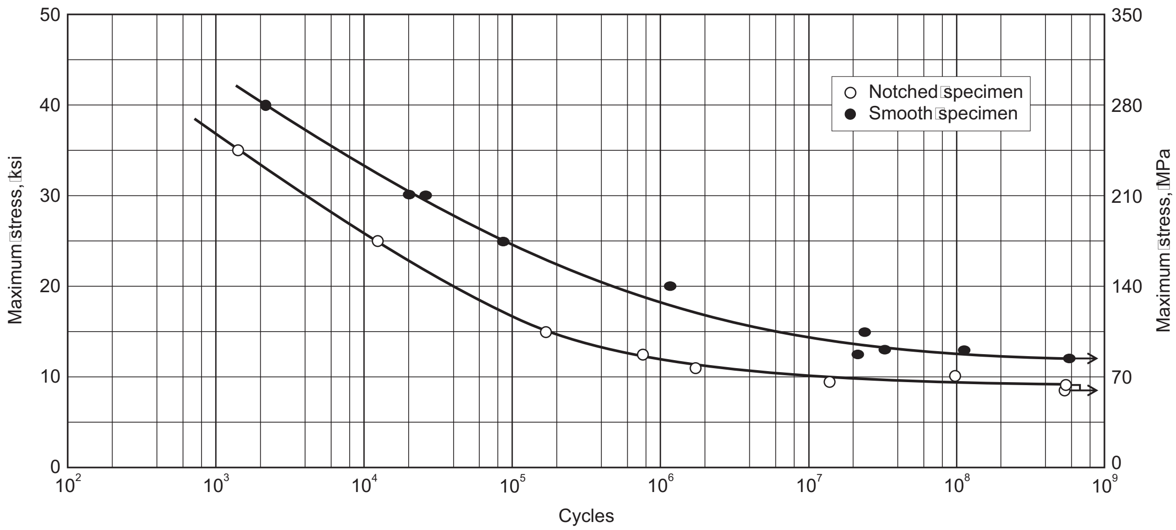

Fig. D6.70 356.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

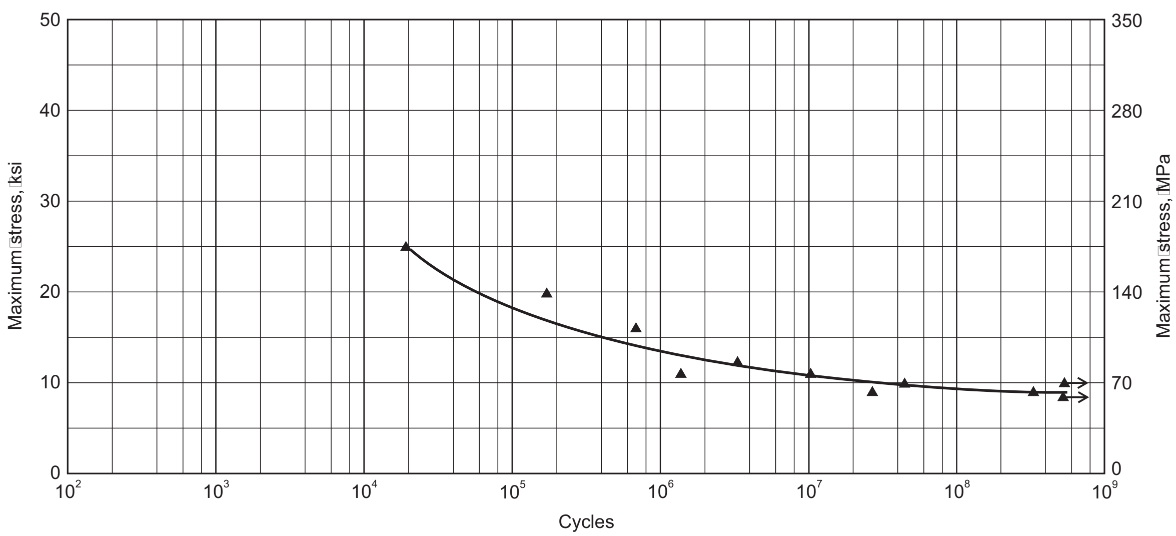

Fig. D6.71 356.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

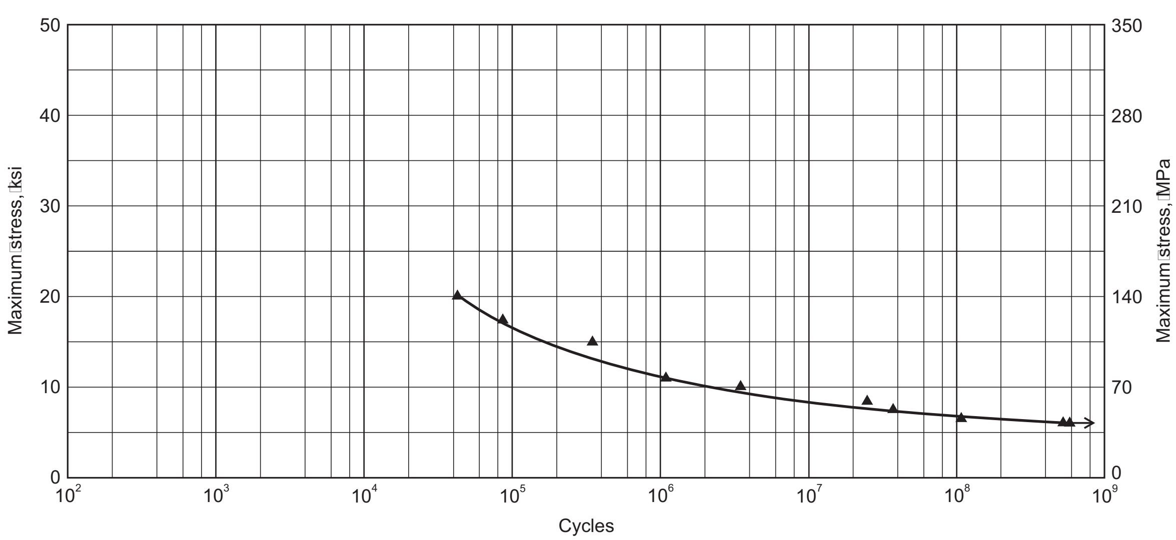

Fig. D6.72 356.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from one lot

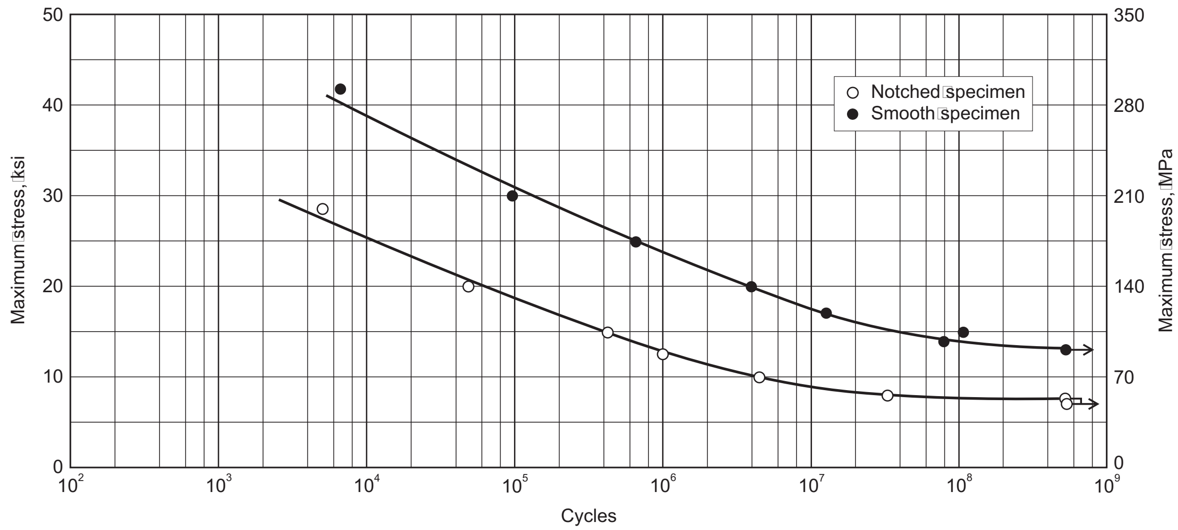

Fig. D6.73 356.0-T61, high-strength plaster cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

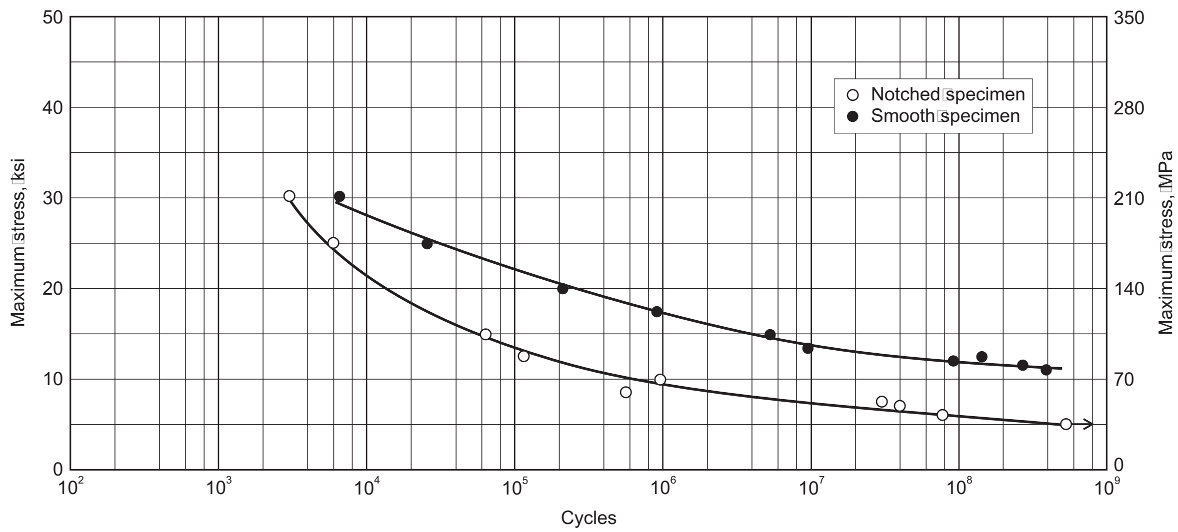

Fig. D6.74 356.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

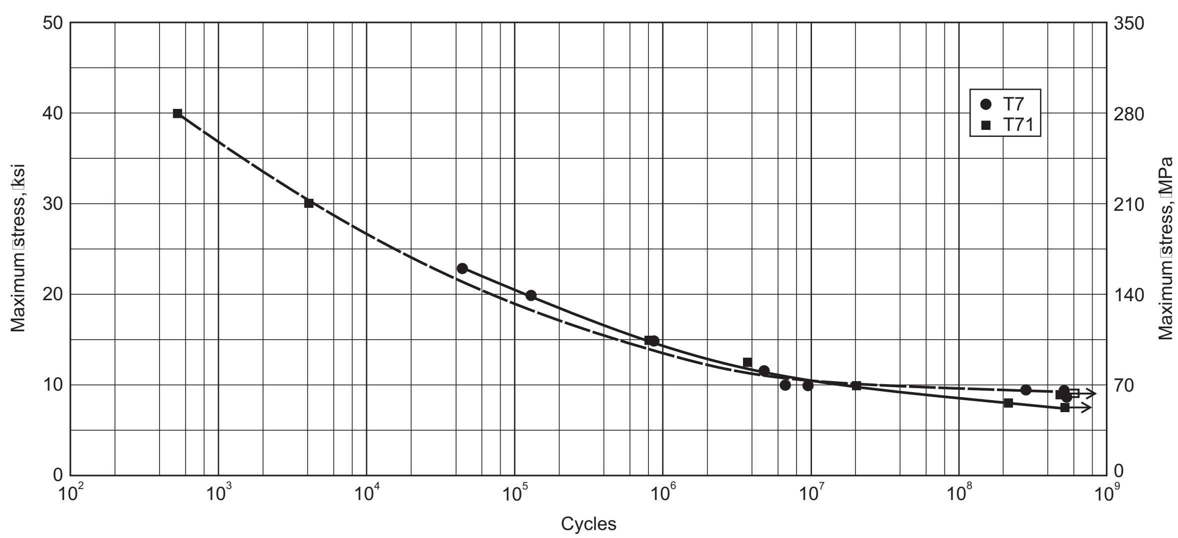

Fig. D6.75 356.0-T7, -T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens with two heat treatments, each from its own lot

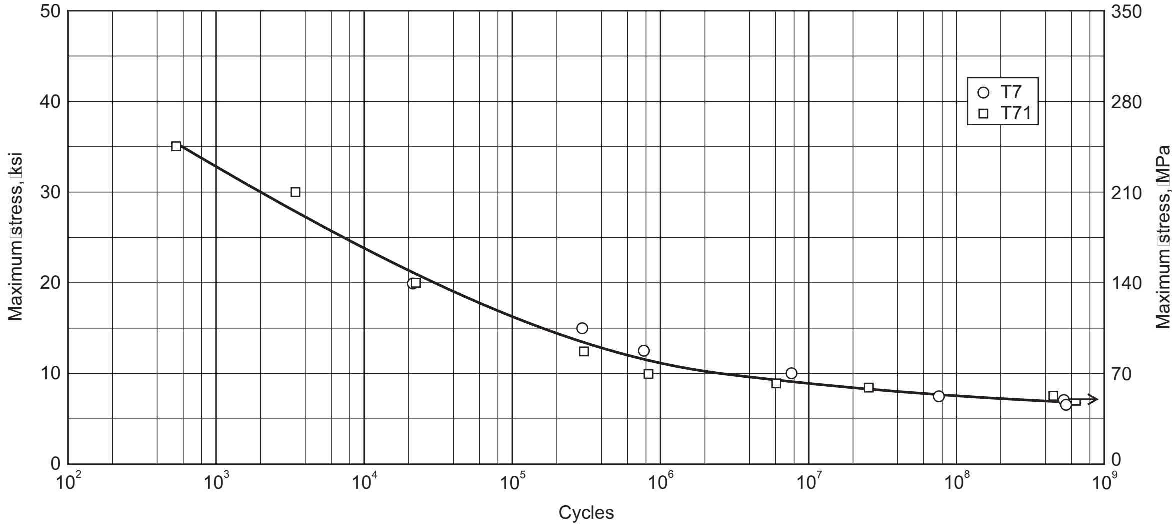

Fig. D6.76 356.0-T7, -T71, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens with two heat treatments, each from its own lot

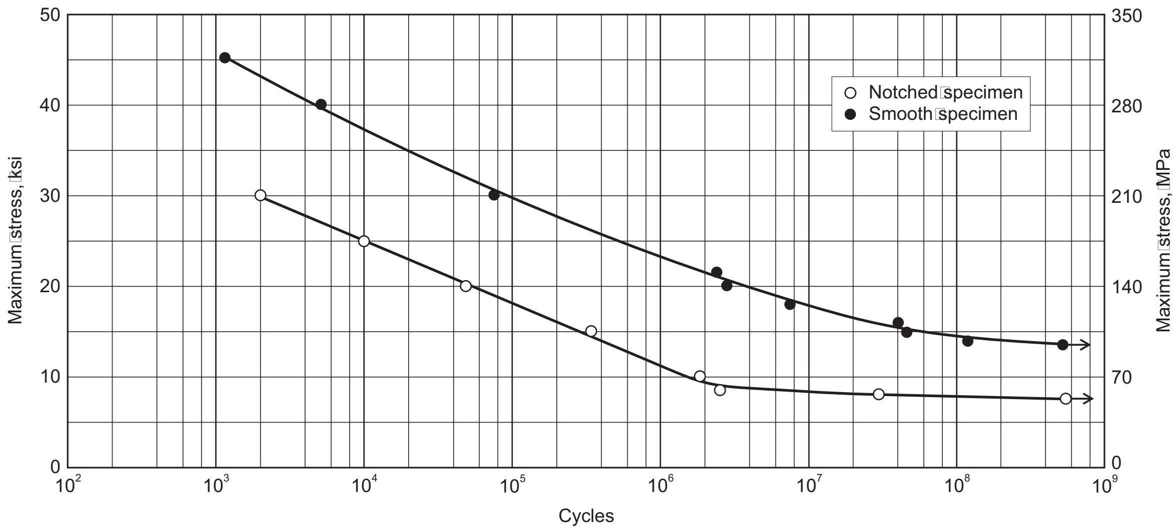

Fig. D6.77 A356.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

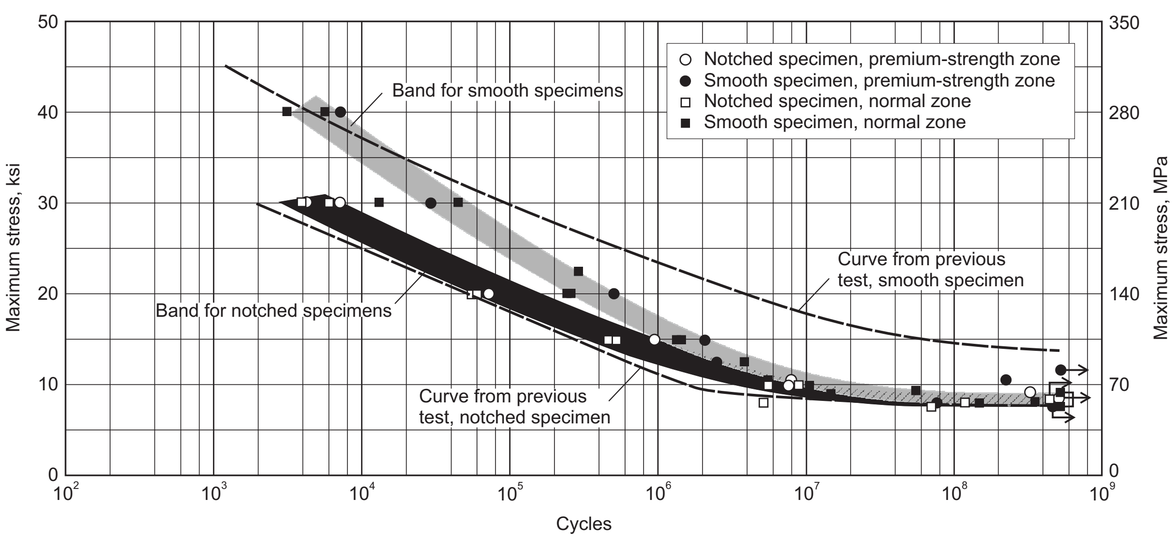

Fig. D6.78 A356.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from premium strength and normal zones. Confidence bands envelope this data. Broken lines are the results from previous tests.

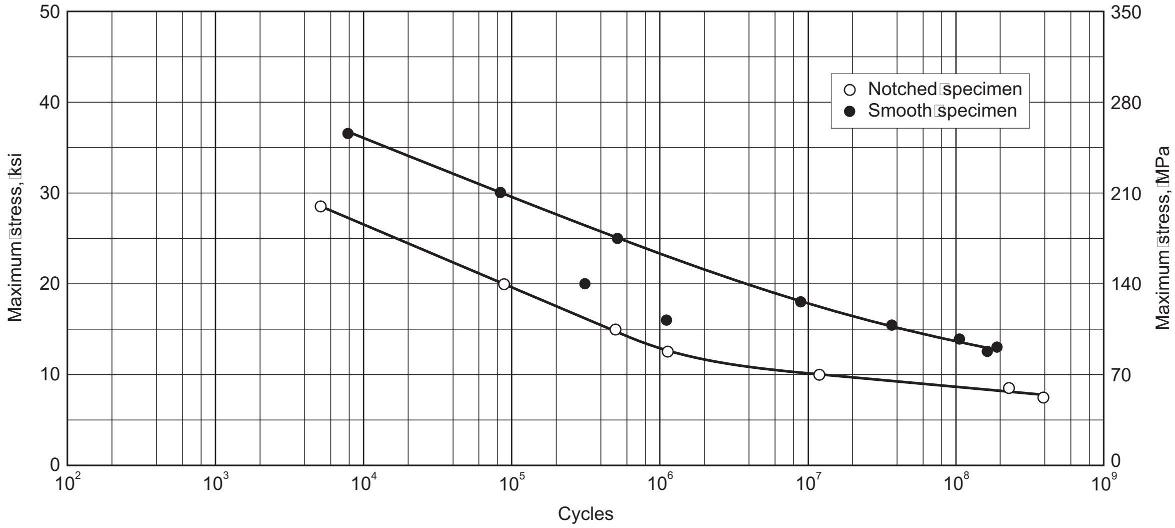

Fig. D6.79 A356.0-T61, high strength plaster cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

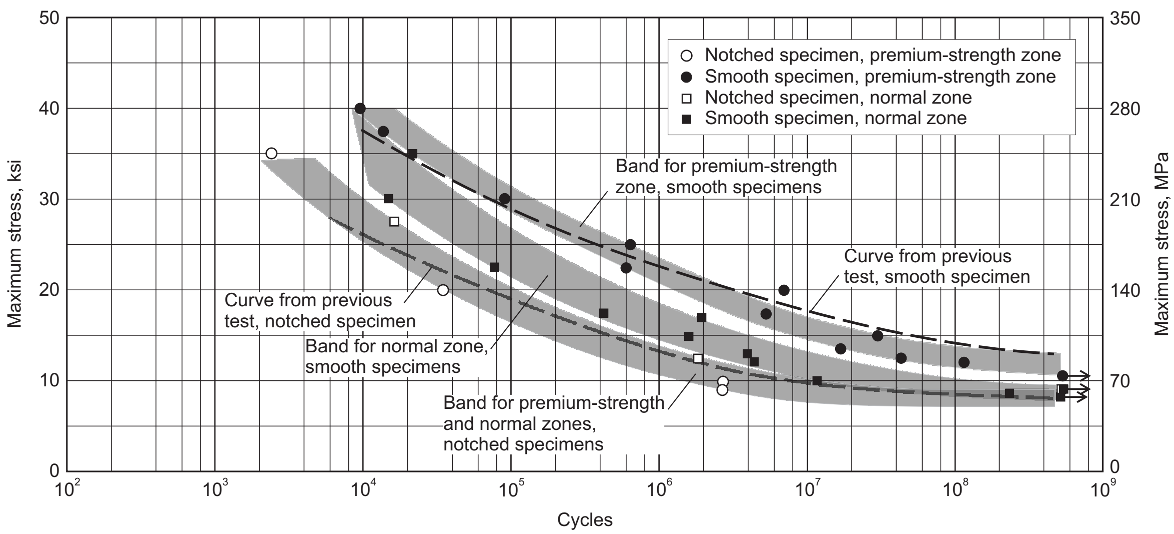

Fig. D6.80 A356.0-T61, high strength plaster cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from premium strength and normal strength zones within the same casting with differing chill practices. Bands envelope this data. Broken lines are the results from previous test, Fig. D6.79.

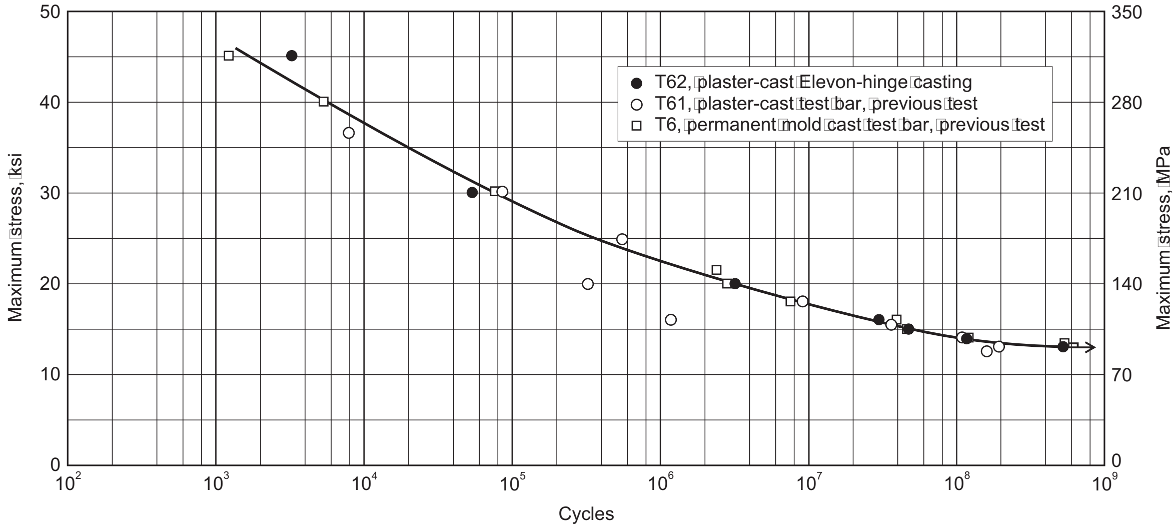

Fig. D6.81 A356.0-T62, high strength plaster cast aluminum casting rotating-beam fatigue curve. Test data for the T62 temper plaster cast Elevon hinge casting is compared to previous T61 plaster cast and T6 permanent mold test data. The T62 temper was 10 h at 340 °F.

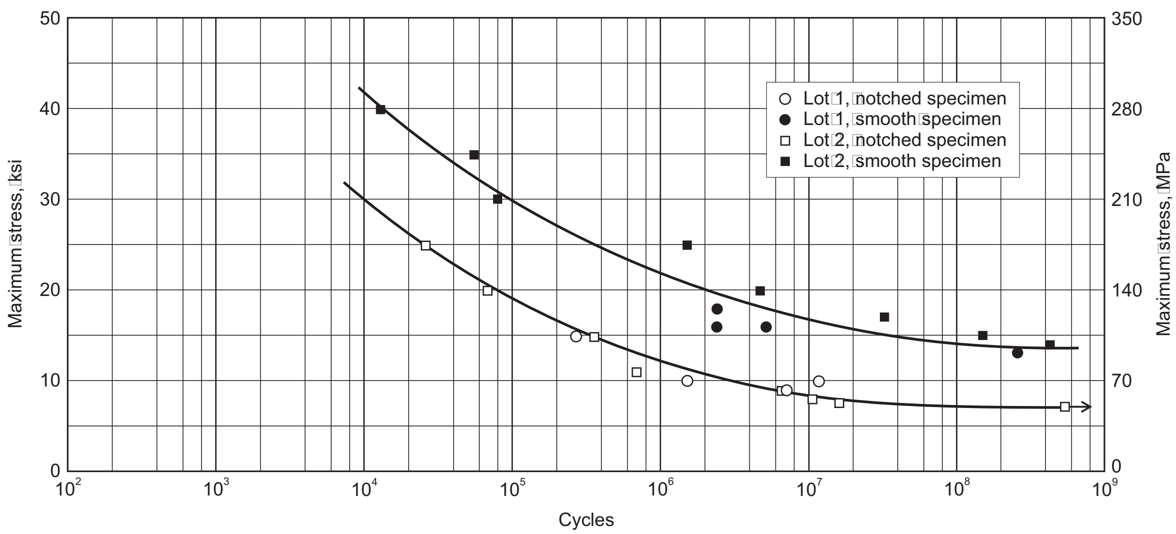

Fig. D6.82 A357.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from two lots. Specimens were machined from cantilever-beam cast test bars.

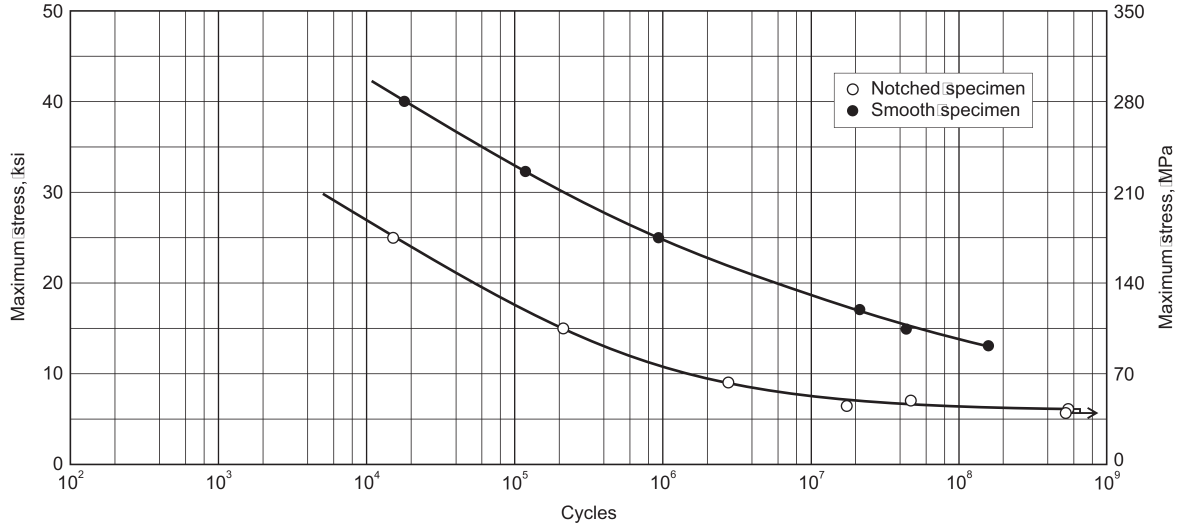

Fig. D6.83 A357.0-T62, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

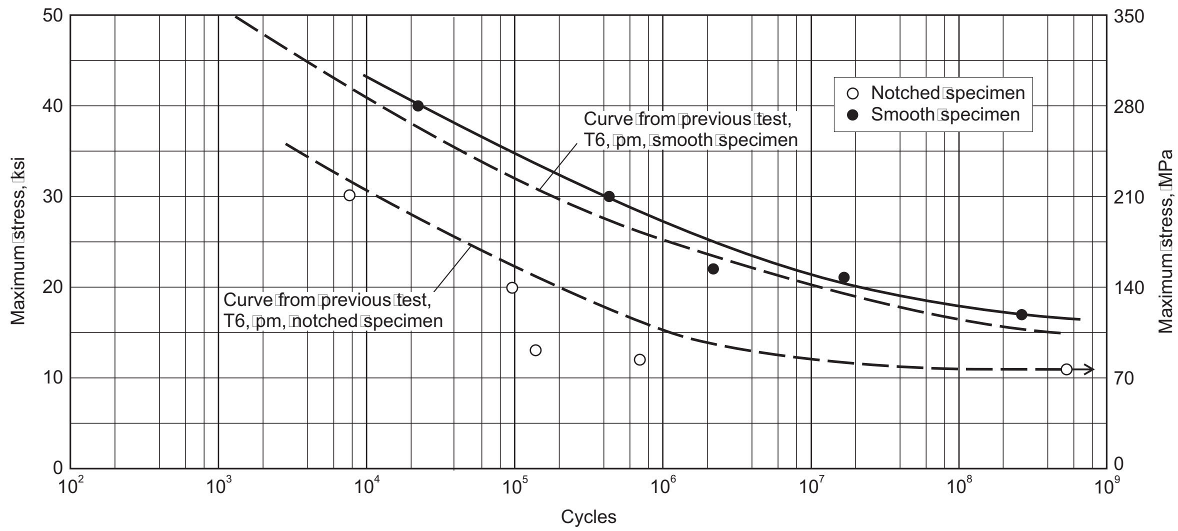

Fig. D6.84 359.0-T61, permanent mold (PM) aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot with T61 temper are compared to prior curves for PM specimens with T6 temper

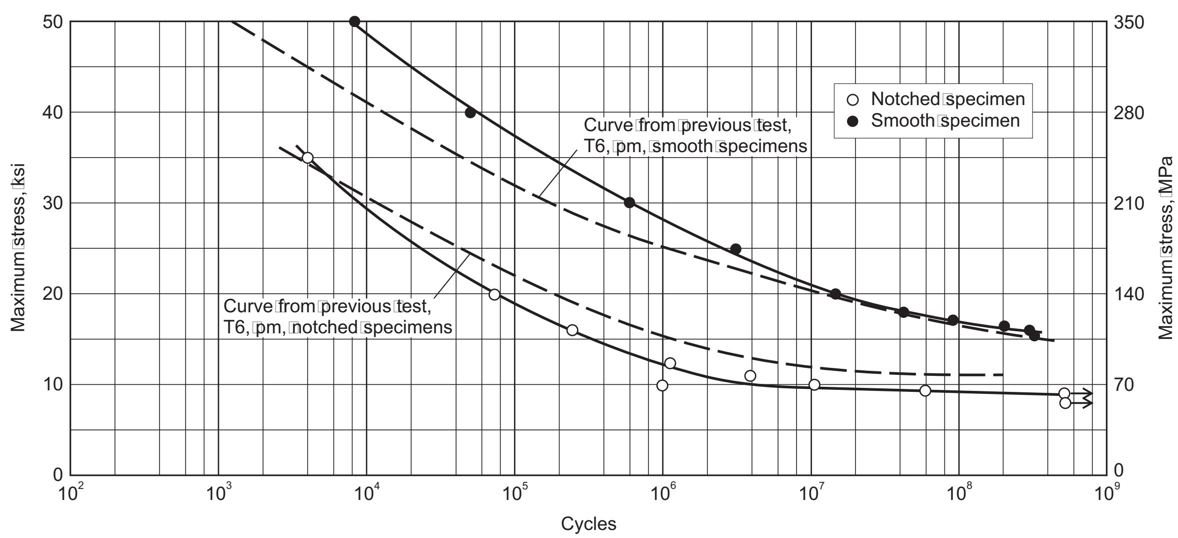

Fig. D6.85 359.0-T62, permanent mold (PM) aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot with T62 temper are compared to prior curves for PM specimens with T6 temper

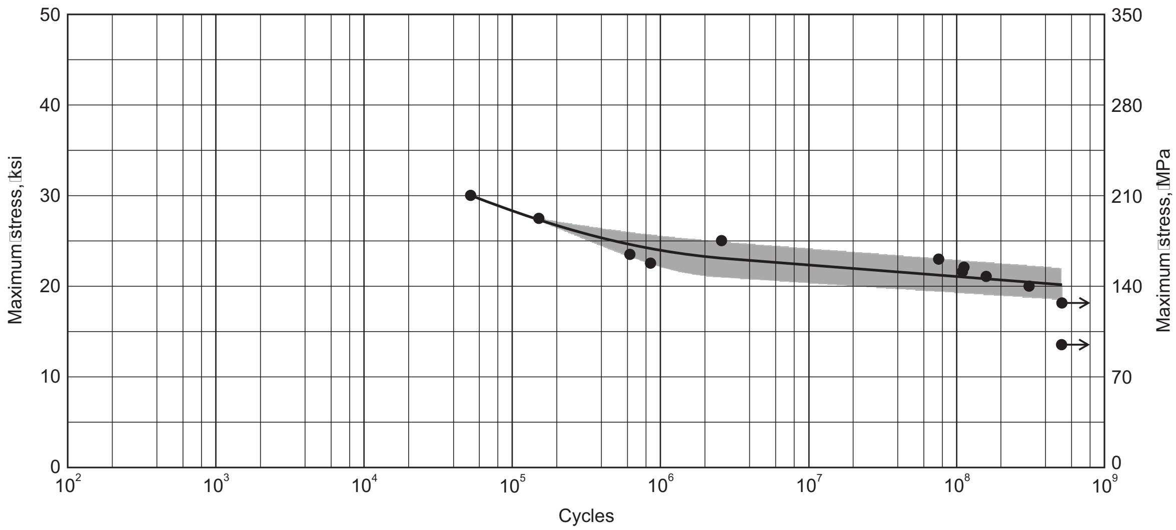

Fig. D6.86 360.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

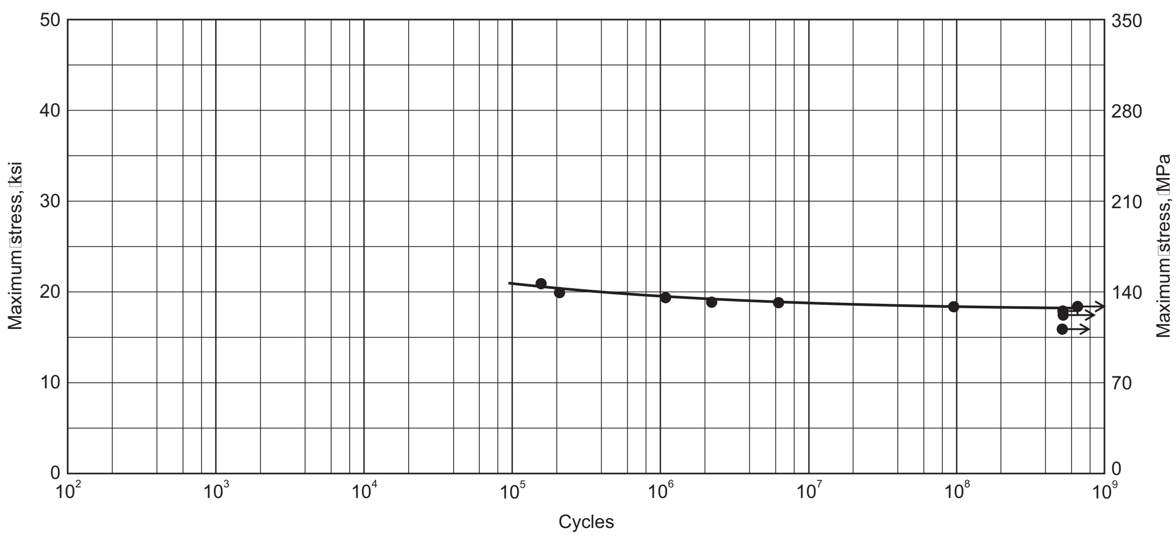

Fig. D6.87 A360.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

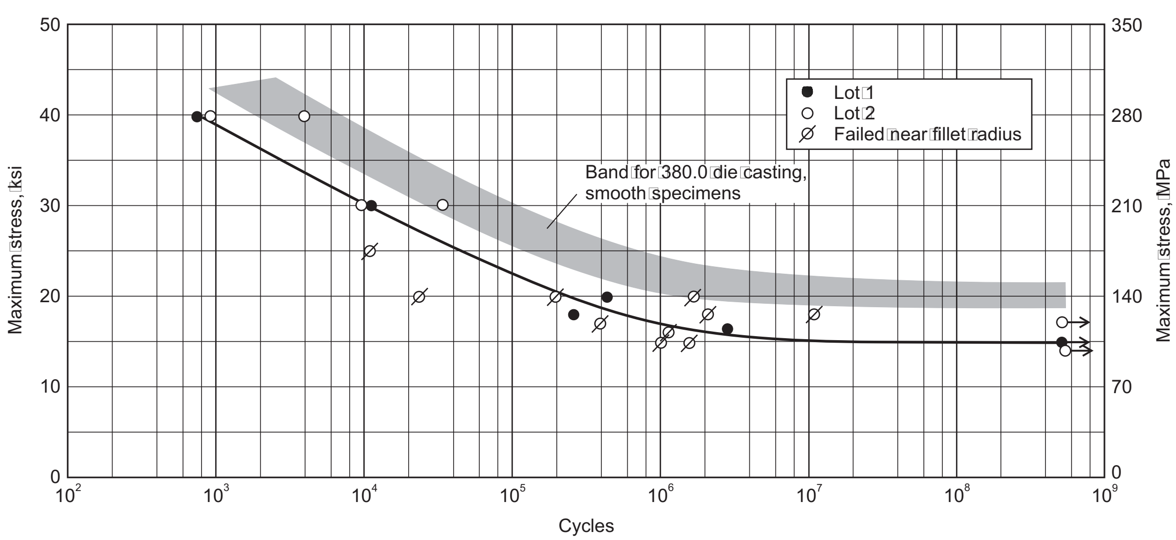

Fig. D6.88 364.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from two lots. Specimen per Fig. A3.4, Appendix 3. Data points with lines indicate failures near fillet radius.

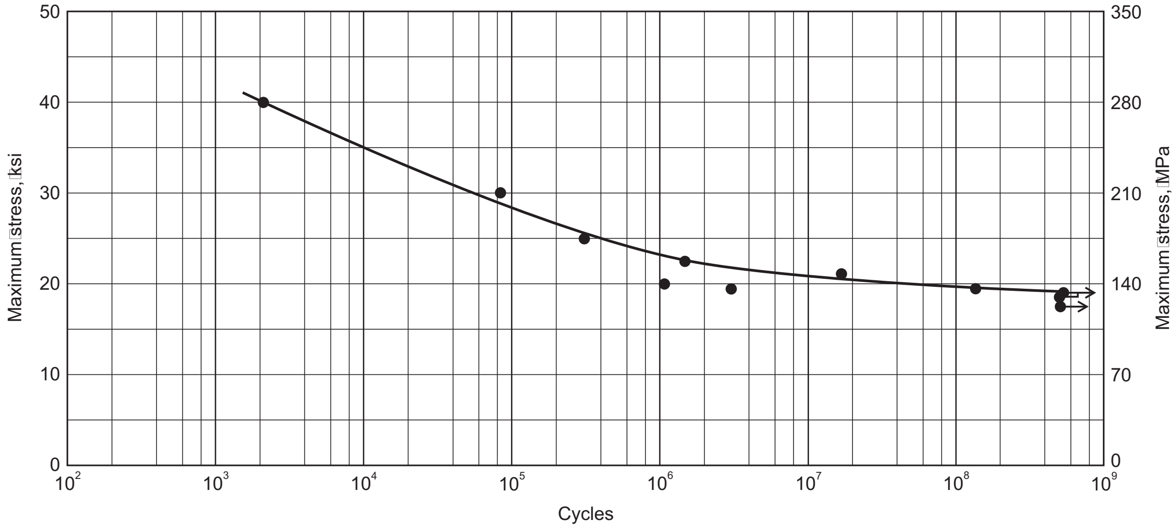

Fig. D6.89 380.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot. Specimen per Fig. A3.4, Appendix 3.

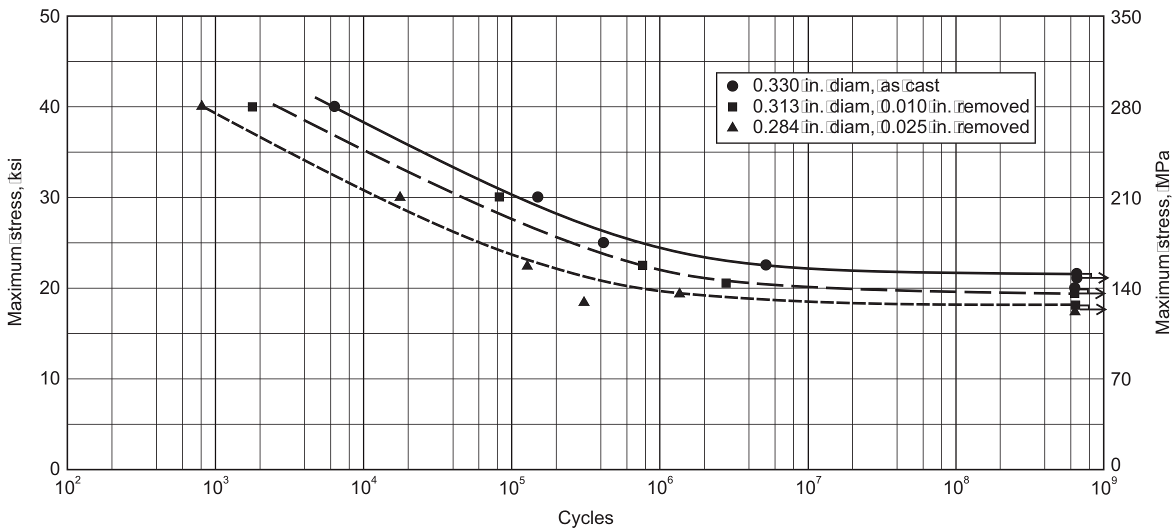

Fig. D6.90 380.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot. Specimen per Fig. A3.4, Appendix 3, as cast. Machined to nominal diameters as noted

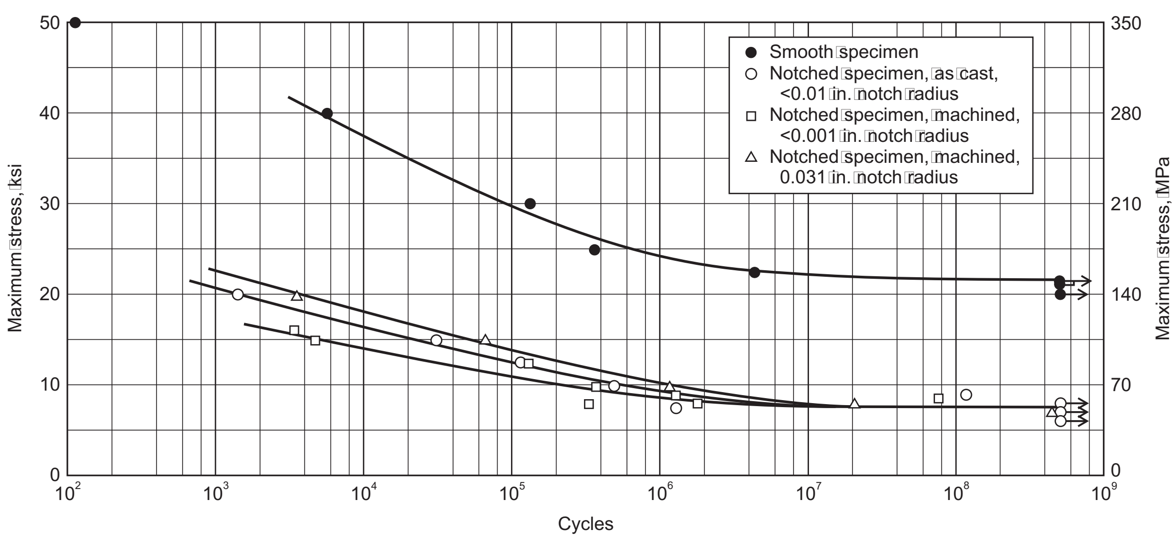

Fig. D6.91 380.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. Notched specimens similar to Fig. A3.2(b), Appendix 3, except notch radius is as noted

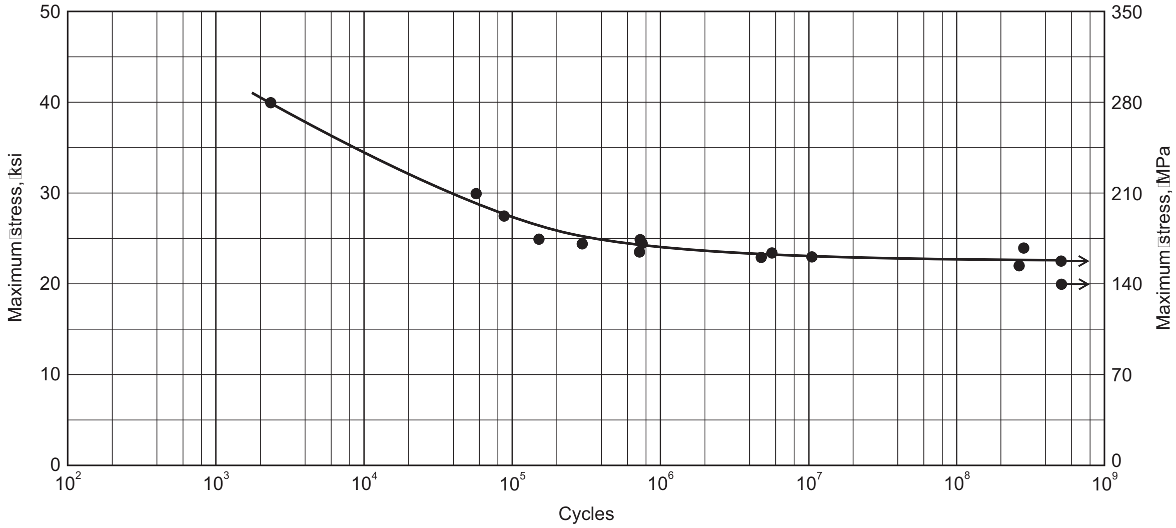

Fig. D6.92 A380.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

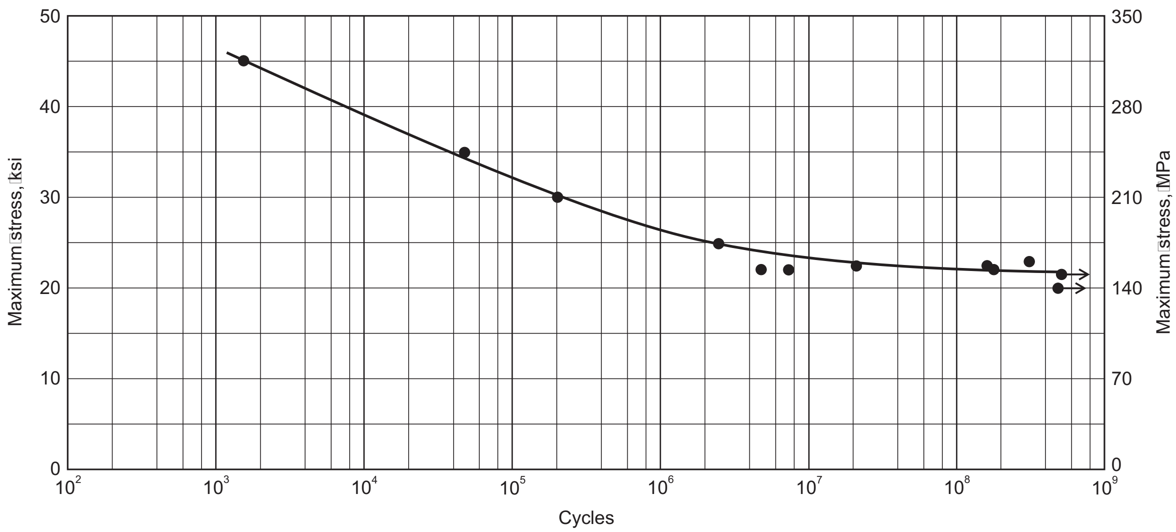

Fig. D6.93 384.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

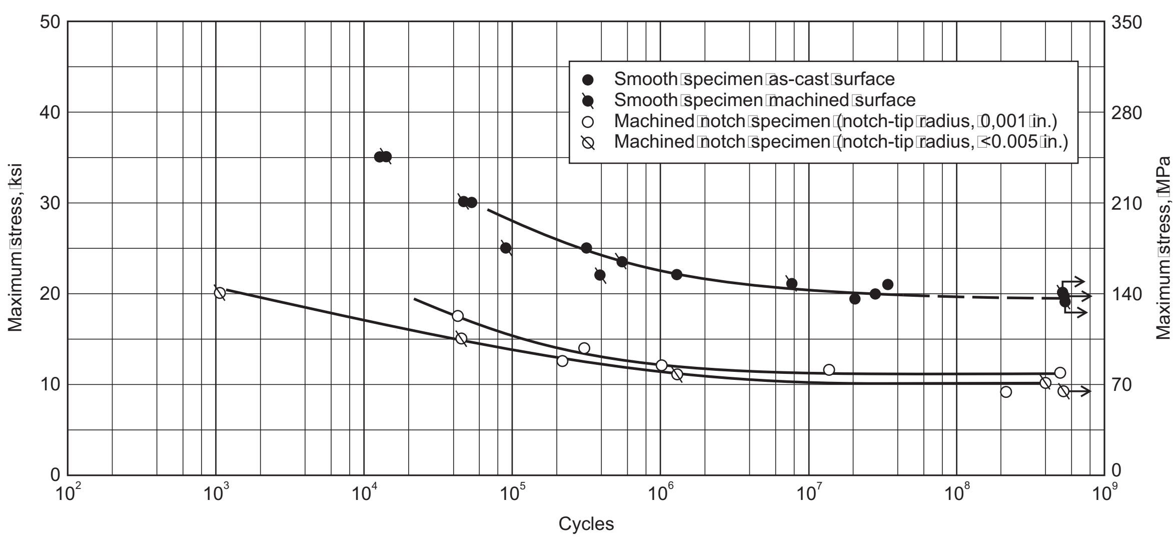

Fig. D6.94 390.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. Smooth specimens per Fig. A3.7, Appendix 3. Notched specimens similar to Fig. A3.2(b), Appendix 3, except notch radius is as noted

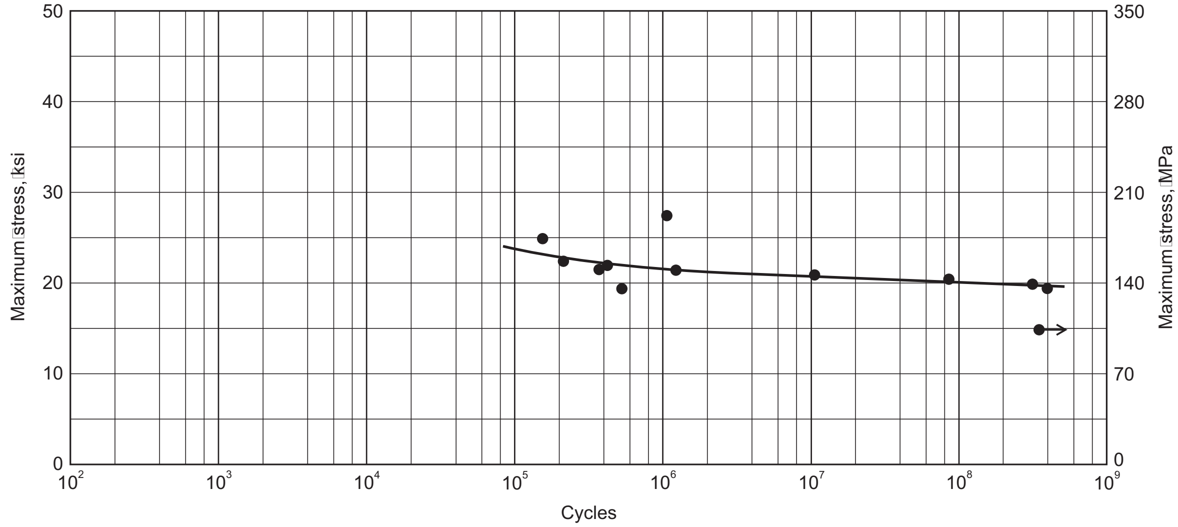

Fig. D6.95 413.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

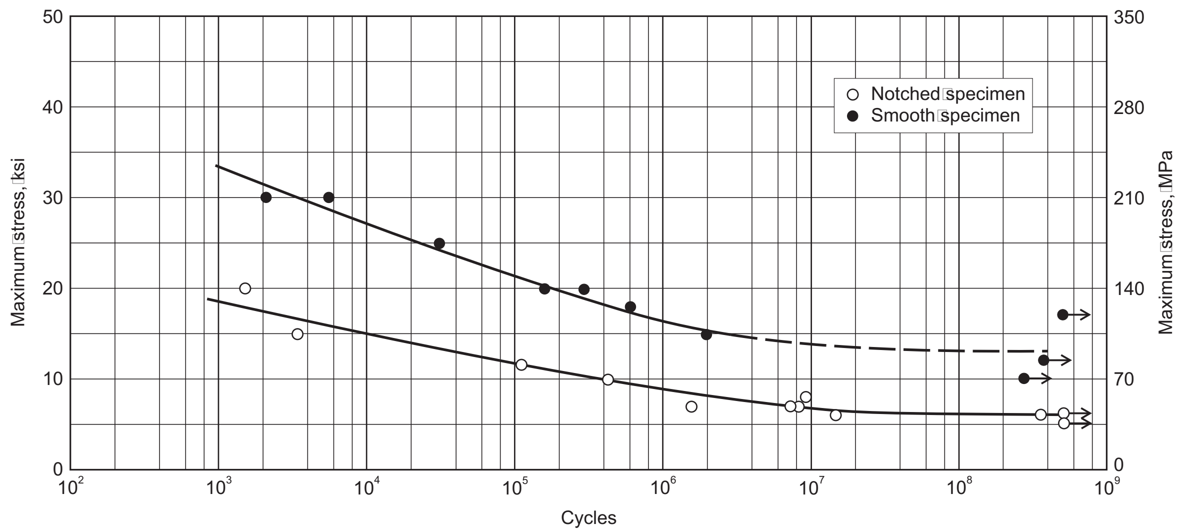

Fig. D6.96 413.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

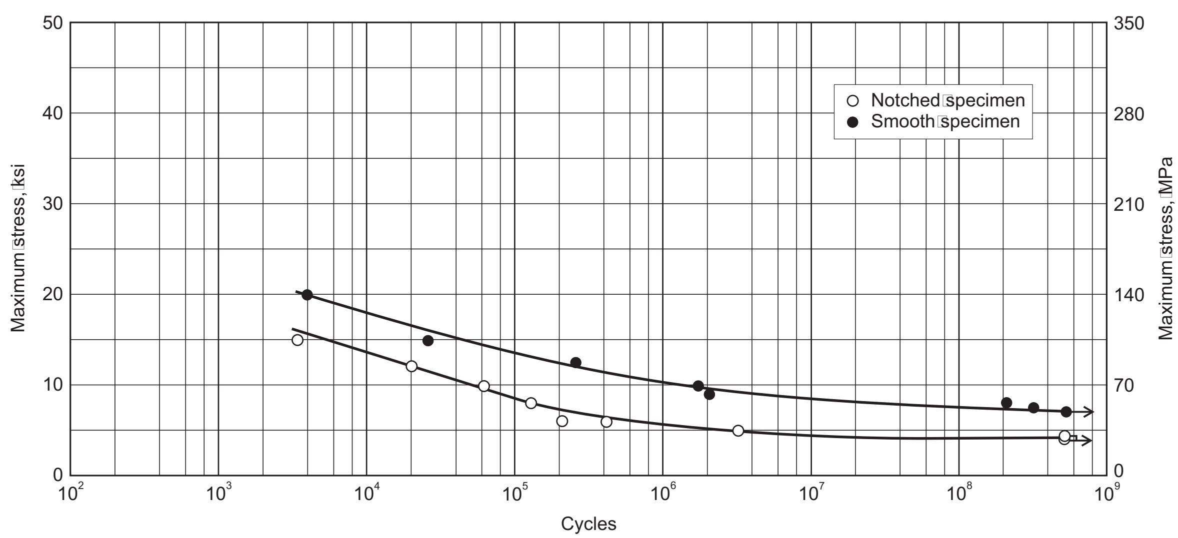

Fig. D6.97 B443.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

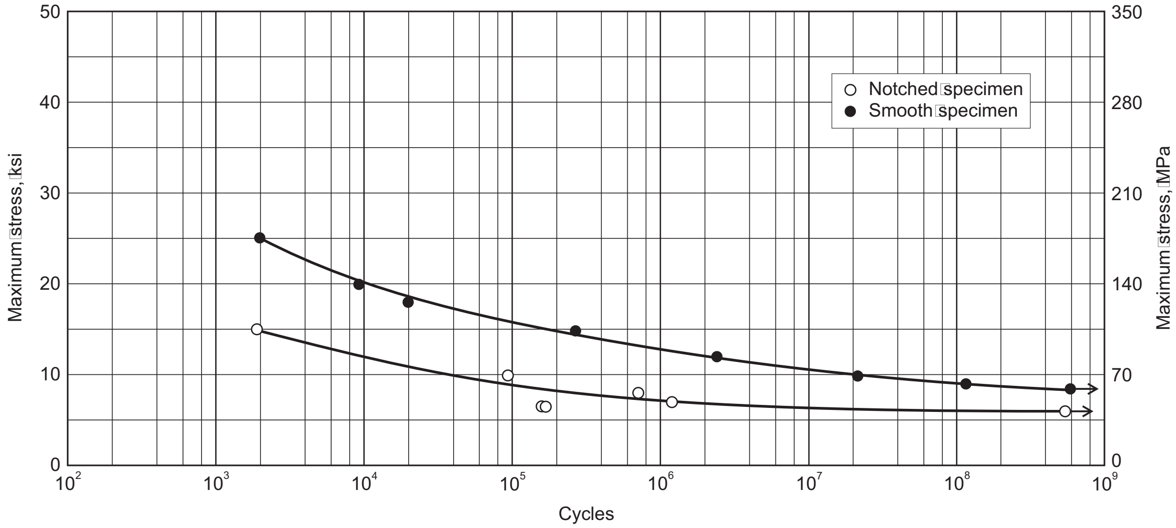

Fig. D6.98 B443.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

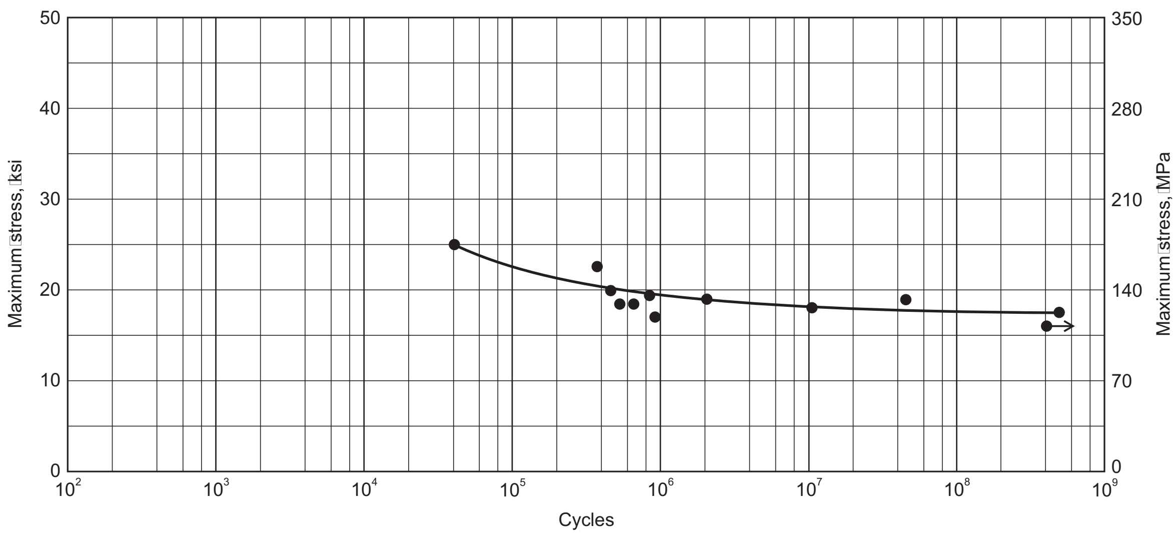

Fig. D6.99 B443.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens per Fig. A3.4, Appendix 3, from one lot

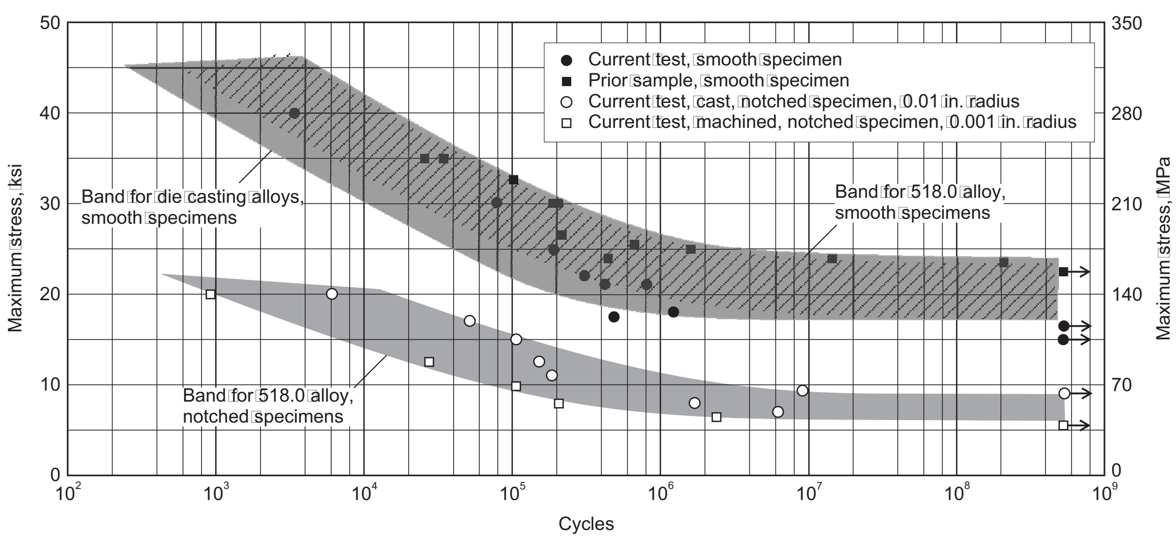

Fig. D6.100 518.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot, with comparison to prior test. Smooth specimens per Fig. A3.4, Appendix 3. Notched specimens similar to Fig. A3.2(b) , Appendix 3, except notch radius is as noted

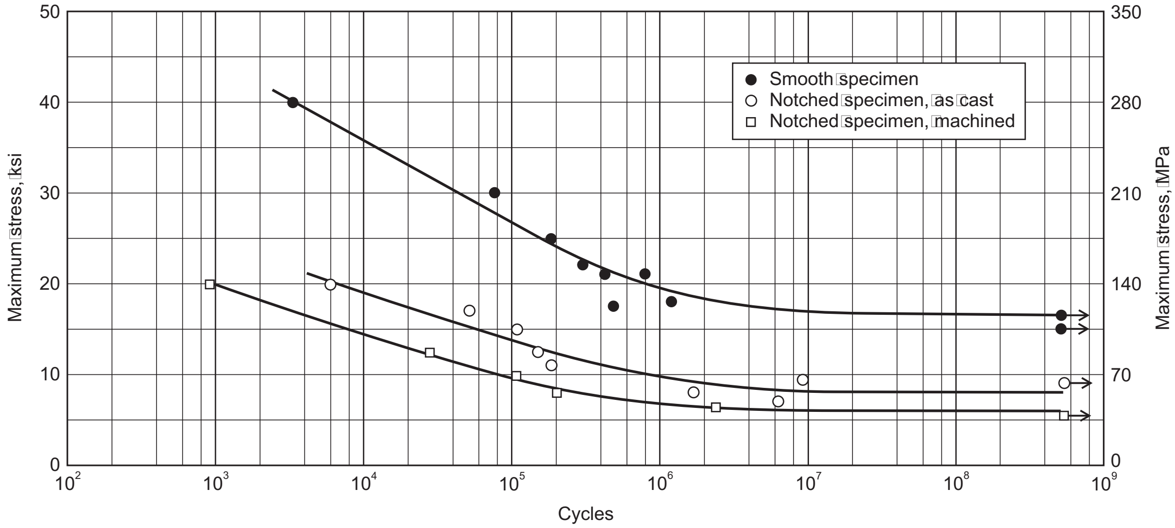

Fig. D6.101 518.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. Smooth specimens per Fig. A3.4, Appendix 3. Machined notched specimens per Fig. A3.2(b), Appendix 3. As-cast notched specimen has radius <0.01 in.

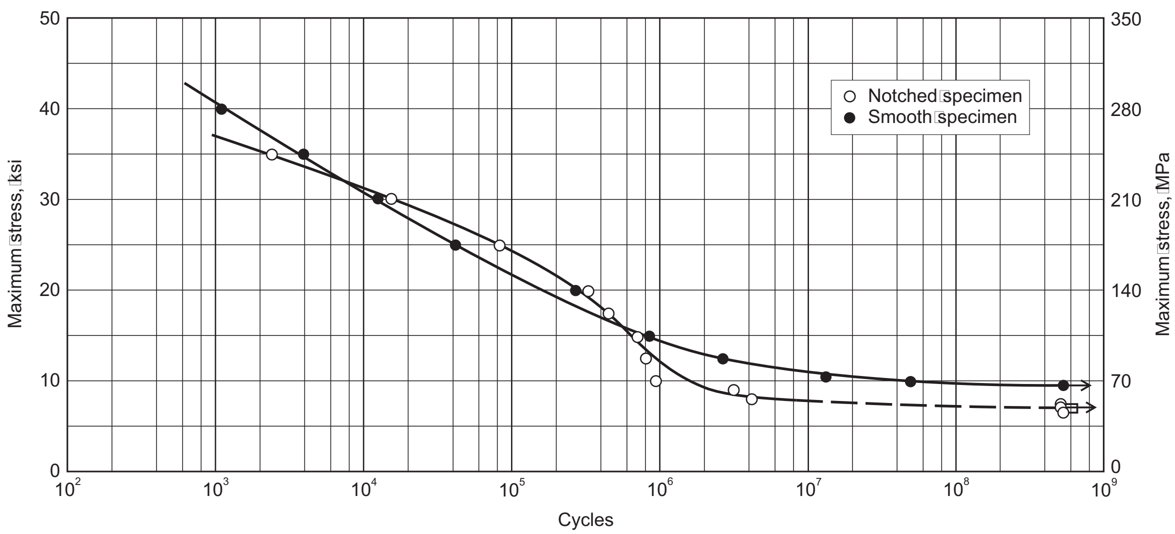

Fig. D6.102 712.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

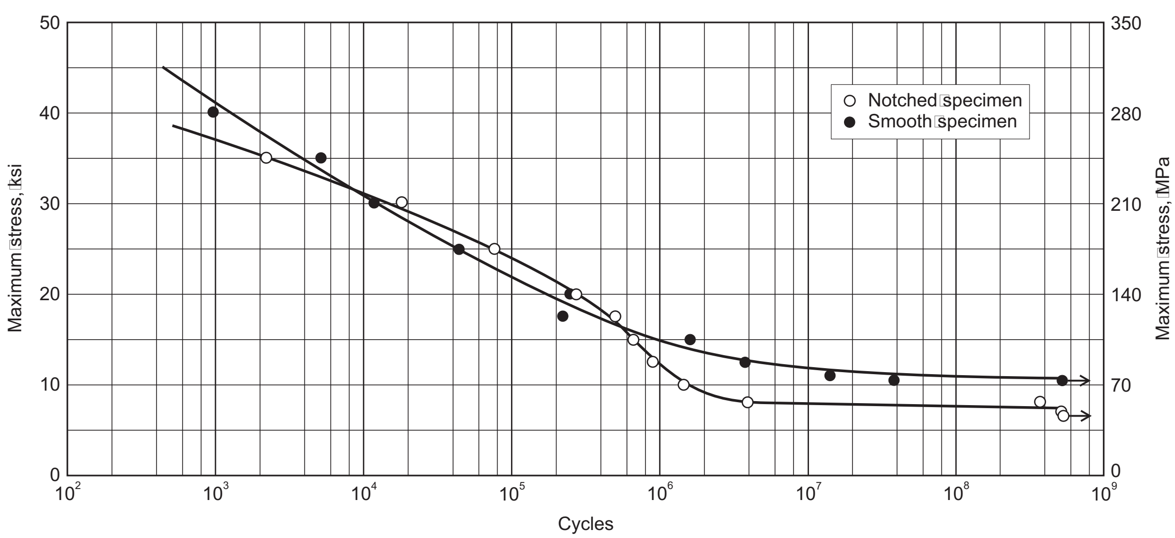

Fig. D6.103 A712.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

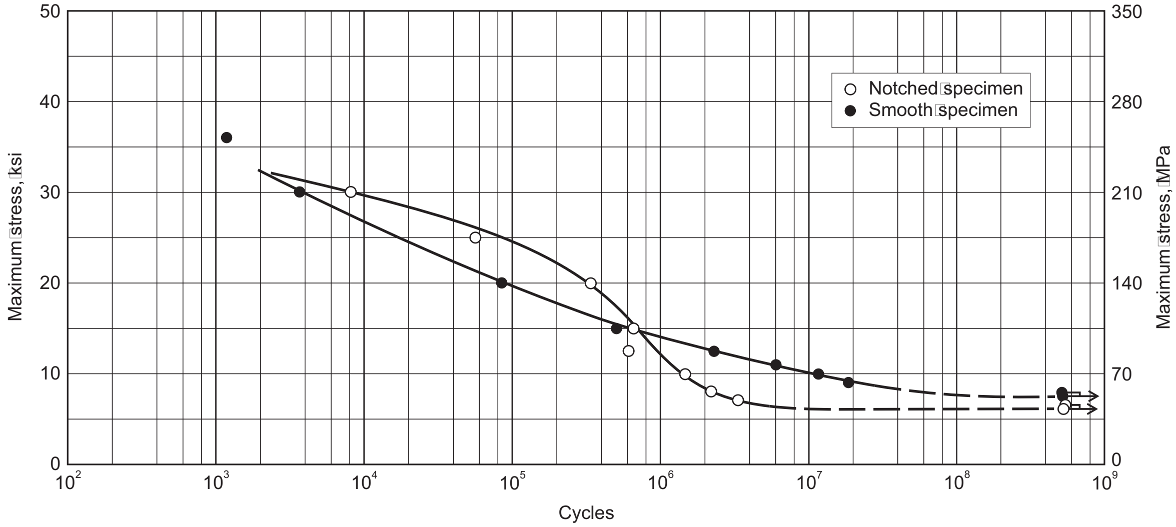

Fig. D6.104 A712.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

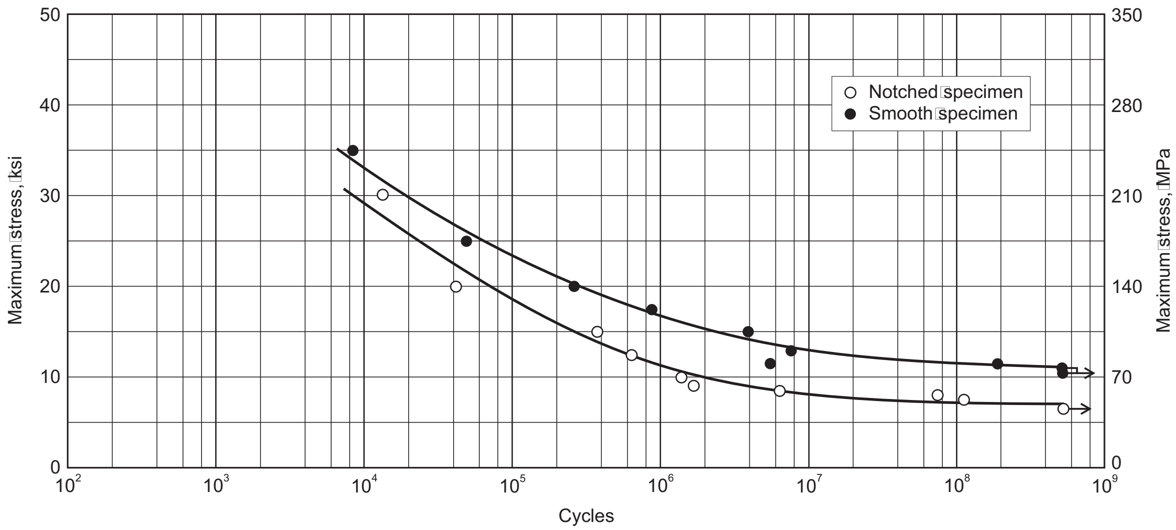

Fig. D6.105 C712.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

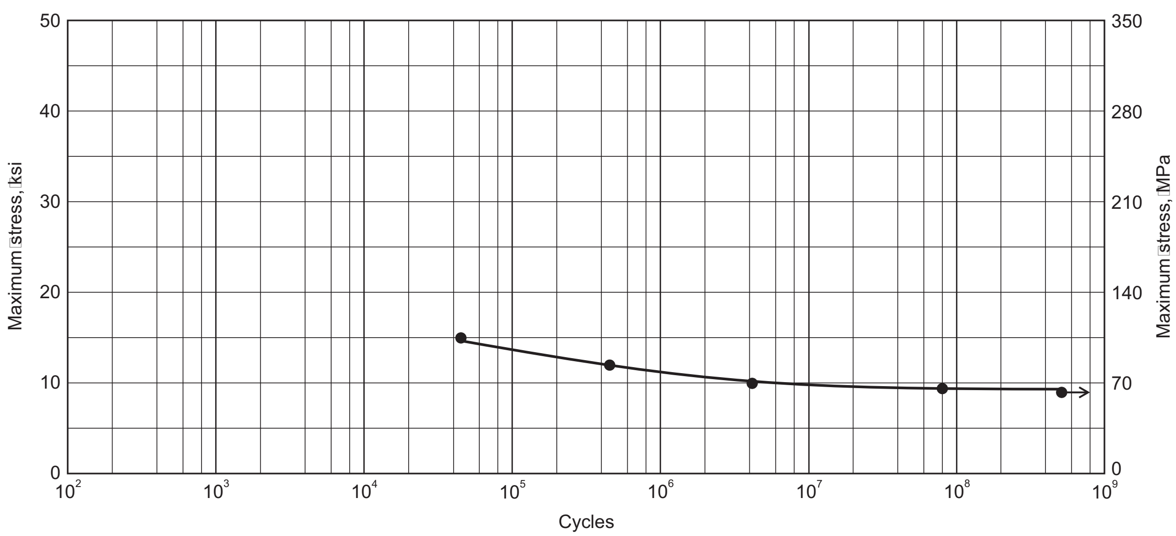

Fig. D6.106 850.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

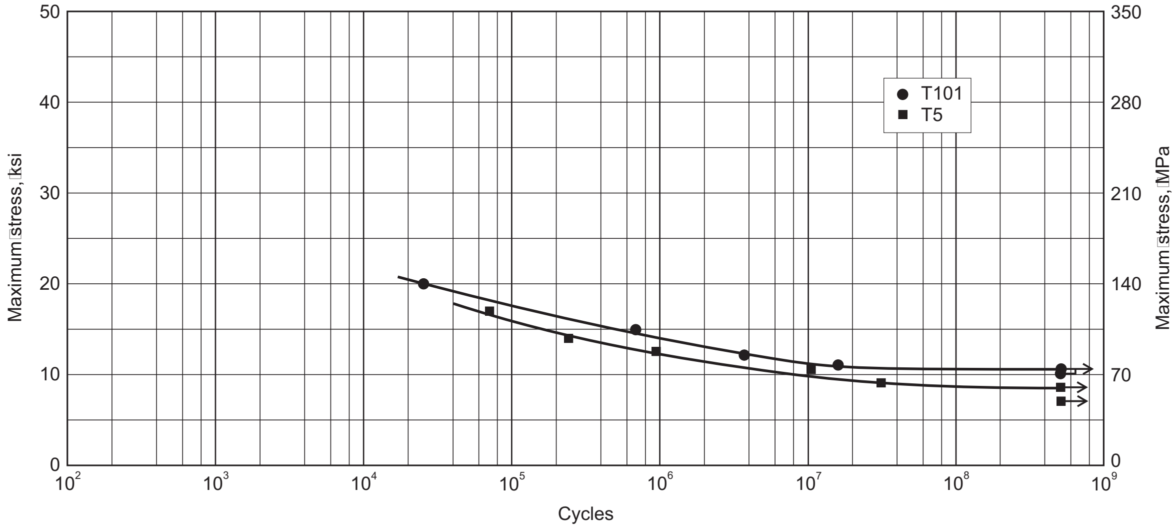

Fig. D6.107 850.0-T101, -T5, permanent mold aluminum casting rotating-beam fatigue curve. Comparison of smooth specimens from two lots, T5 and T101 temper

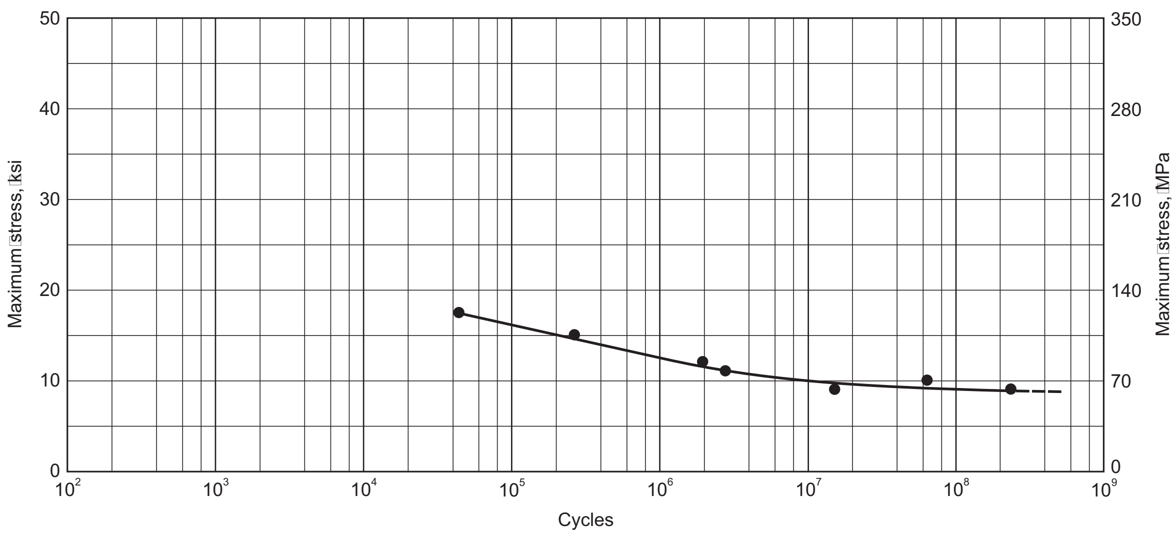

Fig. D6.108 851.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot. Heat treatment: 4 h at 900 °F, boiling water quench, 4 h at 430 °F

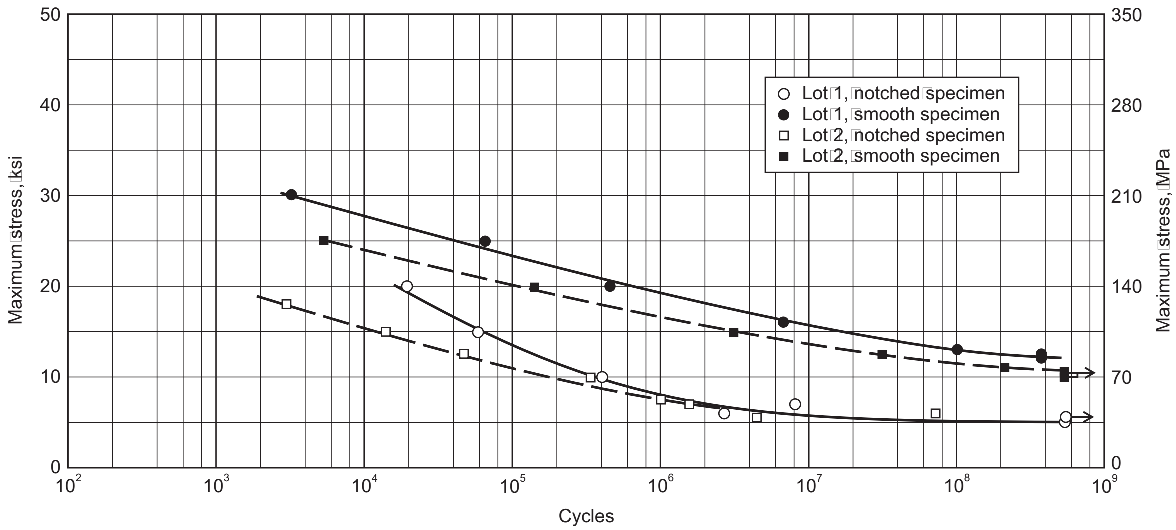

Fig. D6.109 852.0-T5, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from two lots

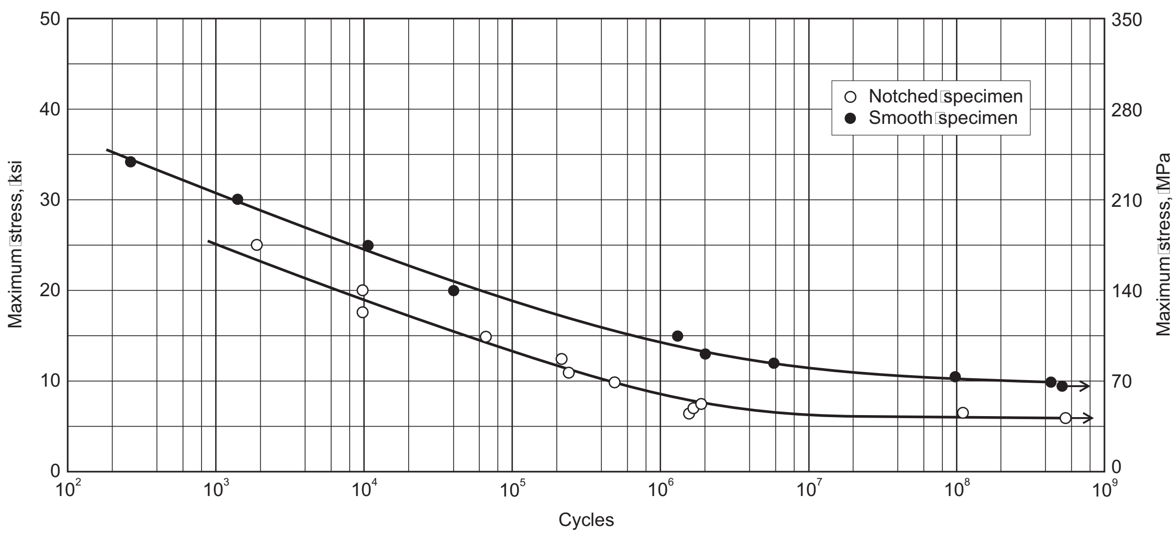

Fig. D6.110 852.0-T5, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

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J.G. Kaufman, E.L. Rooy, p 293-298
DOI:10.1361/aacp2004p293

APPENDIX 1

Glossary of Terms

The following list of terms is associated primarily with cast aluminum products, their production, and their properties. The list is not intended to be exhaustive, including every term likely to be used within the aluminum casting industry, but rather as a resource for readers of this book.

Many of these terms come from the Aluminum Association publication *Aluminum Standards and Data* and casting industry publications of the American Foundry Society (AFS), the North American Die Casting Association (NADCA), and the Non-Ferrous Founders' Society (NFFS). The reader is referred to those societies' publications for more complete terminology for casting and casting processes.

A

age hardening. A process that results in increased strength and hardness as a result of precipitation of hardening phase(s) from solid solution.

aging. Precipitation from solid solution resulting in a change in properties of an alloy, usually occurring slowly at room temperature (natural aging) and more rapidly at elevated temperatures (artificial aging).

alloy. A substance having metallic properties composed of two or more elements.

annealing. Thermal treatment to soften metal by depleting solid solution, coalescing precipitates, and for relieving residual stresses.

anodizing. Forming a controlled oxide coating on a metal surface by electrochemical treatment.

artificial aging. *See* aging.

as-cast condition. Newly produced or unfinished castings. Also describing castings that have not been thermally treated.

B

binder. A material used to bond grains of foundry sand to form a mold or core. It can be cereal, oil, clay, or natural/synthetic resin.

blast cleaning. A process to clean or finish castings by use of an air blast or airless centrifugal wheel that accelerates abrasive particles or metal shot against the surface of castings.

blow hole. A blister that has ruptured and may produce a void. A defect caused by entrapped gases often associated with excessive moisture or volatile reactions with mold or core components.

brazing. Joining metals by fusion of nonferrous alloys that have melting points above 425 °C (800 °F) but lower than those of the metals being joined. This may be accomplished by means of a torch (torch brazing), in a furnace (furnace brazing), or by dipping in a molten flux bath (dip or flux brazing).

brazing rod. A rolled, extruded, or cast round filler metal for use in joining by brazing.

brazing wire. Wire for use as a filler metal in joining by brazing.

buffing. A mechanical finishing operation in which fine abrasives are applied to a metal surface by rotating fabric wheels for the purpose of developing a lustrous finish.

C

casting (noun). An object formed by solidification of molten metal introduced to a mold or dies.

casting (verb). Introducing molten metal into a mold or dies.

casting strains. Strains in a cast metal component resulting from internal stresses created during cooling from solidification temperature.

casting yield. The weight of casting or castings divided by the total weight of metal poured into the mold, expressed as a percent.

centrifugal casting. In the centrifugal casting process, commonly applied to cylindrical castings, a permanent mold is rotated rapidly about the axis of the casting, while a measured amount of molten metal is poured into the mold cavity. Centrifugal force is used to hold the metal against the outer walls of the mold with the volume of metal poured determining the wall thickness of the casting. Conventional permanent mold castings are produced by spinning molds during and after mold filling to enhance filling and to induce internal soundness by centrifugal force.

chill. Metal insert placed in a sand mold to increase localized heat flux. In permanent mold, air, mist, and water are used to selectively cool mold segments.

cleaning. Removal of sand and excess metal from a sand casting, ceramic and excess metal from an investment casting, or excess metal from a die casting.

CO_2 process. Molds and cores, made with sand coated with sodium silicate, which are hardened by permeating the sand with carbon dioxide gas to form a silica gel.

cold shut. A linear discontinuity in a cast surface caused when meeting streams of metal fail to merge prior to solidification.

cold working. Plastic deformation of metal at such temperature and rate that strain hardening occurs.

coloring. A finishing process, or combination of processes, that alters the appearance of an aluminum surface via coating, chemical, and/or mechanical operations.

combination die (multiple-cavity die). A die with two or more different cavities for different castings.

condensation stain. *See* corrosion, water stain.

controlled cooling. Process by which a metal object is cooled from an elevated temperature in a manner that avoids hardening, cracking, or internal damage.

conversion coating. An inorganic pretreatment sometimes applied to a metal surface to enhance coating adhesion and retard corrosion.

core. Separable part of a mold made of sand and a binder to create openings and various specially shaped cavities in sand and semipermanent mold castings. Also drawable metallic mold components in permanent mold and die casting dies.

coring. Chemical segregation across grains that occurs during solidification.

corrosion. The deterioration of a metal by chemical or electrochemical reaction with its environment.

corrosion, galvanic. Corrosion associated with galvanic action between dissimilar conductors in an electrolyte or similar conductors in dissimilar electrolytes. Aluminum will sacrificially corrode if it is anodic (electronegative) to the dissimilar metal. Galvanic corrosion may also occur between dissimilar microstructural features when exposed to an electrolyte.

corrosion, intergranular. Corrosion occurring preferentially at grain boundaries (also termed intercrystalline corrosion).

corrosion, pitting. Localized corrosion resulting in small pits or craters in a metal surface.

corrosion, stress. Failure, usually intergranular, resulting from the simultaneous interaction of sustained tensile stresses below the yield point and exposure to a corrosive environment. The term is often abbreviated SCC (stress-corrosion cracking).

coupon. A casting prolongation from which a test specimen may be prepared without damaging the casting.

cutoff. Removal of gates, risers, and other excess metal from a casting.

D

defect. Any structural discontinuity that affects acceptability or performance capabilities.

die (in casting). Metal form(s) used to produce a die casting, permanent mold casting, a lost foam, wax, or core pattern.

die casting (noun). A casting produced by the pressure die casting process.

die casting (verb). Injecting molten metal under pressure into a mold, which is formed by metal dies. In Europe, any casting produced in a metal mold.

die casting, cold chamber. Die casting process in which the metal injection mechanism is not submerged in molten metal.

die casting, gravity. Term used in Europe for producing a casting by pouring molten metal (gravity pouring) into a metal mold, with no application of pressure. In the United States, this is the permanent mold casting process.

die casting, high pressure. A die casting process in which the metal is injected under high pressure in either cold or hot chamber die casting machines. In the United States, this is simply die casting. High-pressure die casting and low-pressure die casting are terms commonly used in Europe to differentiate between what in the United States would be called, respectively, pressure die casting and gravity permanent molding.

die casting, hot chamber. Die casting process in which the metal injection mechanism is submerged in molten metal.

die number. The number assigned to a die for identification and cataloging purposes and which usually is assigned for the same purpose to the product produced from that die.

dimensional stability. Ability of a casting to remain unchanged in size and shape.

double shear notch. *See* notch, double shear.

draft. Taper on the sides of a die or mold impression to facilitate removal of castings, or patterns from dies or molds.

dry sand molding. Dry sand molds are made by many different processes. Sand mixed with binders that cure by baking is one form of dry sand mold; other more common dry sand molding techniques use sand with binders that can be cured by chemical or catalytic reaction induced by mixing with the sand or by blowing gases through the mold after it is formed.

ductility. The property measuring permanent deformation before fracture by stress in tension.

E

elastic limit. The highest stress that a material can withstand without permanent deformation. For most practical application purposes, the elastic limit is the yield strength.

electrical conductivity. The capacity of a material to conduct electrical current. For aluminum, this capacity is expressed as a percentage of the International Annealed Copper Standard (IACS), which has a resistivity of $\frac{1}{58}$ ohm-mm^2/m at 20 °C (68 °F) and an arbitrarily designated conductivity of one.

electrical resistivity. The reciprocal of electrical conductivity. The electrical resistance of a body of unit length and unit cross-sectional area or unit weight. The value of $\frac{1}{58}$ ohm-mm^2/m at 20 °C (68 °F) is the resistivity equivalent to the IACS for 100% conductivity.

elongation. The property measuring permanent deformation before failure. The percentage increase in length between gage marks that results from stressing a specimen in tension to failure.

endurance limit. The limiting stress below which a material will withstand a specified number of cycles of stress.

expendable pattern casting. Casting process that employs a foam polystyrene or other plastic pattern-and-sprue assembly in a loose sand mold. Molten metal, poured into the sprue, vaporizes the pattern and replaces it to become the casting when it so-

lidifies. This process is also widely referred to as lost-foam casting.

F

fatigue. The tendency for a metal to break under conditions of repeated cyclic stressing below the ultimate tensile strength.

feeder. *See* riser.

fillet. A concave junction between two surfaces.

finish. The characteristics or relative smoothness or roughness of an as-cast or machined surface.

flash. A protrusion that forms when metal, in excess of that required to fill the mold impression, penetrates the parting plane.

flash line. A line left on a casting where flash has been removed.

flow line. Visible pattern on the surface of a casting corresponding to the pattern of metal flow in the mold.

fracture toughness. A generic term for measuring the resistance to low-ductility extension of a crack; alternatively, the energy-absorbing capability of a metallurgical structure under stress leading to failure. The term is sometimes restricted to results of a fracture mechanics test, such as ASTM E 399 for plane-strain fracture toughness, K_{Ic}, which may be directly applicable in design. Fracture toughness may also be measured in relative terms by notch tensile or tear testing.

G

gas porosity. Casting defects caused by entrapped gases or by hydrogen precipitated during solidification.

gate. Passage(s) in the runner system through which molten metal enters the mold cavity. Sometimes used as a general term to indicate the entire assembly of connected columns and channels carrying molten metal to the casting cavity.

gated patterns. Patterns with integral gating.

gating system. The complete assembly of sprues, runners, gates, and risers in a mold through which metal flows to the casting cavity.

grain refiner. An alloy or salt mixture comprising components that form nuclei for the heterogeneous nucleation of aluminum grains during solidification.

grain size. A measure of crystal size usually reported in terms of average diameter in millimeters, grains per square millimeter, or grains per cubic millimeter.

green sand. Clay-bonded molding sand containing water.

green sand molding. The mold is composed of a prepared mixture of sand, clay, and water, usually with other additives to suppress mold reactions, aid in sand separation after casting, or alter surface quality. The mold is not cured or dried and therefore is known as a green (uncured) sand mold.

gross to net weight ratio. The ratio of total weight contained by the casting and gating system and casting weight.

H

hardener. An alloy of aluminum and one or more added elements for use in making alloying additions. Also referred to as master alloy.

hardness. Resistance to plastic deformation, usually by indentation. The term also may refer to stiffness or temper, or to resistance to scratching, abrasion, or cutting. Brinell hardness of aluminum alloys is obtained by measuring the permanent impression in the material made by a ball indenter 10 mm in diameter after loading at 500 kgf (4.903 kN) for 15 s and dividing the applied load by the area of the impression. Rockwell and other hardness tests with smaller indenters provide less accurate measurements in aluminum.

heat treatable alloy. An alloy that may be strengthened by dissolving and reprecipitating soluble phases.

heat treating. Heating and cooling castings to controllably alter material properties.

heat treat stain. A discoloration due to nonuniform oxidation of the metal surface during solution heat treatment.

high-pressure molding. A term applied to certain types of sand molding machines in which high-pressure air is used to produce extremely hard, high-density molds from green sand.

holding temperature. The temperature at which the liquid casting alloy is held in the furnace before and during casting. Usually set as the lowest temperature consistent with mold filling.

hot cracking. A crack in a casting that occurs at elevated temperature caused by thermal contraction of the part during or immediately after solidification.

hot isostatic pressing (HIP). A process that uses high pressures at elevated temperatures to close interior voids in castings or consolidate P/M products.

hot shortness. The tendency of an alloy to crack during or immediately after solidification.

I

impregnation. A process for making castings pressure tight by treatment with liquid synthetic resins or other sealers.

inclusion. Nonmetallic contamination of the metal structure.

in-gate. The portion of the gating system that connects runners to the mold cavity.

ingot, remelt. A cast form of known composition intended and suitable for remelting.

injection. The process of forcing molten metal or plastic into a die cavity.

inoculant. Material which, when added to molten metal, modifies the structure, and thereby changes the physical and mechanical properties to a degree not explained on the basis of the change in composition resulting from its use. The term is normally applied to ferrous alloys, but is sometimes used to describe grain refinement and other additions in aluminum casting alloys.

insert. A metal component that is placed in the mold allowing molten metal to be cast around it. The component becomes an integral part of the casting.

inspection lot. *See* lot, inspection.

investment casting. *See* investment molding.

investment molding. The process also is known as the lost wax process. Molds are produced by dipping wax or thermoplastic patterns in a fine slurry to produce as smooth a surface as possible. The slurry is air dried and redipped several times using less

expensive and coarser, more permeable refractory until the shell is of sufficient thickness for the strength required to contain molten metal. Investment molds also are produced as solid molds by placing the pattern assembly in a flask, which is then filled with a refractory slurry and air dried. The molds then are put into a furnace where the wax or plastic is removed by melting or volatilization. Molten metal is poured into the molds while the molds are still superheated, thus making it possible to pour very thin wall sections. A metal pattern die is used to produce the wax or plastic expendable patterns. Investment molding produces casting of superior surface finish, dimensional accuracy, and without parting fins or seams.

L

layout sample. A prototype or production casting used to determine conformance to dimensional requirements.

lost foam casting. The casting process, also known as full-mold, polycast, cavity molding, evaporative pattern, or expendable pattern casting, is one in which a polystyrene pattern is vaporized by molten metal during the metal pour (*see also* expendable pattern casting).

lot, heat treat. Material traceable to one heat treat furnace or, if heat treated in a continuous furnace, charged consecutively during a finite period.

lot, inspection. (1) For non-heat-treated tempers, an identifiable quantity of castings of the same part submitted for inspection at one time. (2) For heat treated tempers, an identifiable quantity of castings of the same part traceable to a heat treat lot or lots and submitted for inspection at one time. In each case, the inspection lot is usually defined by a molten metal batch or continuous furnace operation of common chemistry and fixed maximum quantity.

low-pressure casting. A casting process in which air or gas pressure is applied to a sealed holding furnace from which molten metal is forced through a feed tube into the mold cavity.

M

master alloy. *See* hardener.

mechanical properties. Those properties of a material that are associated with elastic and inelastic deformation when force is applied, or that involve the relationship between stress and strain. They include modulus of elasticity, tensile strength, yield strength, and ductility.

microporosity. Microscopic interdendritic porosity in castings caused by shrinkage and/or gas evolution.

misrun. Failure to completely fill the mold cavity.

modification. Promotion of a fibrous or lamellar structure in hypoeutectic aluminum-silicon alloys by modifying additions or solidification rate.

modulus of elasticity. The ratio of stress to corresponding strain throughout the range of proportionality.

mold. A shaped cavity into which molten metal is poured to produce a solidified casting.

mold cavity. The space in a mold that is filled with liquid metal to form the casting. Metal external to the mold cavity such as gates and risers are not considered part of the mold cavity.

multiple cavity mold. A mold in which more than one part of the same design is produced.

N

natural aging. *See* aging.

nondestructive testing. Testing or inspection procedure that does not destroy or damage the product being inspected.

nonfill. Failure of metal to completely fill the mold cavity.

non-heat-treatable alloy. An alloy that cannot be significantly strengthened through postsolidification thermal treatment.

notch toughness. A general term describing the ability of a material to deform plastically locally in the presence of stress-raisers (either cracks, flaws, or design discontinuities) without cracking, and thus to redistribute loads to adjacent material or components.

notch-yield ratio, NYR. The ratio of the tensile strength of a notched specimen (the notch-tensile strength) to the tensile yield strength of a material. This provides a measure of notch toughness, the ability of a material to plastically deform locally in the presence of a stress-raiser, and thus to redistribute the stress. For aluminum alloys, it is measured in accordance with ASTM E 338 and E 602.

O

offset. Yield strength by the offset method is computed from a load-strain curve obtained by means of an extensometer or manual plotting. A straight line is drawn parallel to the elastic portion of the load-strain curve. The most common method offsets +0.2 (0.002 mm/mm, or 0.002 in./in., of gage length). The load at the point where this line intersects the curve is used in the yield strength calculation.

oxide discoloration. As-cast surface coloration caused by elemental effects or differences in the composition and form of the oxide.

P

pattern. A wood, metal, plastic, wax, or other replica of a casting that is used to form the cavity in a mold into which molten metal is poured to form a cast part. A pattern has the same basic features as the part to be cast, except that it is made proportionately larger to compensate for shrinkage due to the contraction of the metal during cooling after solidification.

permanent mold casting. A gravity or countergravity casting process that uses a metal or graphite mold that can be used repeatedly to produce cast parts of the same design.

physical properties. Intrinsic properties that pertain to the physical behavior of a material. Physical properties include specific gravity, electrical and thermal conductivity, and thermal expansion characteristics.

plane strain. The condition in which the stresses in all three directions may be significant (i.e., a triaxial stress condition may prevail), and the strains in one principal direction are essentially uniform or zero, usually through the thickness. This condition is approximated at the tip of a crack, where the strain through the thickness of a component along the crack front is zero.

porosity. Voids in a casting usually caused by shrinkage or hydrogen.

precipitation hardening. *See* aging.

precipitation heat treating. S*ee* aging.

prolongation. A physical extension of a casting that provides the source of test coupons without affecting the integrity of the part.

Q

quality. An indefinite measurement of structural integrity.

quench crack. Failure caused by stresses induced during rapid cooling or quenching.

quenching. Rapid cooling of a metal from elevated temperature.

R

radiographic inspection. Examination of soundness by radiography.

radiography. The use of radiant energy in the form of x-rays or gamma rays for nondestructive examination of opaque objects, such as castings, to produce graphic records that indicate the comparative soundness of the object being tested.

refinement. Phosphide nucleation of primary silicon in hypereutectic aluminum-silicon alloys.

riser. Sometimes referred to as a head or feeder. A strategically located volume of thermally and/or pressure differentiated molten metal that forms a reservoir from which volumetric losses caused by shrinkage as the casting solidifies can be compensated.

runner. That portion of the gating assembly that conveys molten metal from the sprue to in-gates.

runner system. Also called gating; the set of channels in a mold through which molten metal travels to the mold cavity; includes sprues, runners, gates, and risers.

S

sample. A part, portion, or piece taken for purposes of inspection or test as representative of the whole.

sand castings. Castings produced in sand molds.

sand mold. A mold formed from chemically or naturally bonded sand.

semisolid casting. Also referred to as semisolid forging, thixocast, or forge casting, it is a process in which metal at a temperature between the liquidus and the solidus is pressed into closed dies. Billet for this process are produced by solidification with inductive or mechanical stirring. Versions include simplified techniques for final solidification from partially solidified structures.

shear strength. The maximum stress that a material is capable of sustaining in shear. In practice, shear strength is considered to be the maximum average stress computed by dividing the ultimate load in the plane of shear by the original area subject to shear.

shell cores. Cores produced from thermosetting sand blends with thicknesses controlled by the thermal cycle.

shell molding. Shell molds are made from a mixture of sand and thermosetting resin binder. Shell molds are backed by loose sand.

shell mold process. A process in which resin-coated sand is deposited on a heated pattern, bonding it to form a hardened shell about 10 to 20 mm (0.40 to 0.80 in.) thick. Two mating shells are glued together to make a precision mold to produce a casting with excellent dimensional accuracy and a smooth surface texture.

shrinkage. Contraction that occurs when metal cools from liquid to solid and in the solid state from solidification to room temperature.

solution heat treating. Heating an alloy at a suitable temperature for sufficient time to allow soluble constituents to enter into solid solution where they are retained in a supersaturated state after quenching.

specimen. A sample taken for evaluation of some specific characteristic or property.

sprue. The vertical portion of the gating system through which molten metal first enters the mold.

squeeze casting. Also known as liquid metal forging or forge casting, it is a casting process by which molten metal solidifies under hydraulic pressure. Other squeeze casting process variations include the insertion of cores under pressure during solidification, cast-forge, and a hinged/displacement technique for casting large thin-walled parts.

stabilizing. Overaging to achieve dimensional stability.

stress. Force per unit of area. Stress is normally calculated on the basis of the original cross-sectional dimensions. The three kinds of stresses are tensile, compressive, and shear.

stress-corrosion cracking (SCC). *See* corrosion, stress.

T

tear resistance. A general term describing the resistance of a material to crack propagation under static loading, in either an elastic stress field (brittle fracture) or a plastic stress field (tearing). Like fracture toughness, it is generally used in connection with crack growth, not crack initiation. Tear resistance measured by unit propagation energy from a tear test made in accordance with ASTM B 871.

temper. For castings, the material condition produced by thermal treatment or a statement of the as-cast condition.

tensile strength. In tensile testing, the ratio of maximum load to original cross-sectional area. Also termed ultimate tensile strength or ultimate strength.

tolerance. Allowable deviation from a nominal or specified dimension.

U

ultimate tensile strength. *See* tensile strength.

unit propagation energy, UPE. A measurement of energy required to propagate a crack under stress, expressed in in.-lb/in.^{2} It is measured in a tear test (ASTM E 871) as amount of energy required to propagate a crack across a unit area in a tear specimen, in terms of the total energy to propagate the crack divided by the nominal crack area (i.e. the original net area of the specimen). Unit propagation energy provides a relative measure of fracture toughness.

V

vacuum casting process. A process in which metal is drawn into the casting cavity by vacuum pressure applied to the mold cavity. Alternatively, the application of vacuum to the die cavity in pressure die casting and placing the mold under vacuum before pouring in investment and other casting processes.

W

welding. Joining two or more pieces of aluminum by applying heat or pressure, or both, with or without filler metal, to produce a localized union through fusion across the interface. Cold welding is a solid-state welding process in which pressure is used at room temperature to produce coalescence of metals with substantial deformation at the weld.

welding rod. A rolled, extruded, or cast round filler metal for use in joining or repairing by welding.

welding wire. Wire for use as filler metal in welding.

wrought product. A product formed by mechanical working by such processes as rolling, extruding, and forging.

Y

yield strength. The stress at which a material exhibits transition from elastic to plastic deformation.

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